NITROGEN AND BIOMASS DISTRIBUTION, AND NITROGEN AND WATER
UPTAKE PARAMETERS FOR CITRUS

By

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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During the last two decades, microirrigation and fertigation have become
commonplace in Florida citriculture. Concurrently, competition for water and nitrate
contamination of ground water have become greater concerns. Information on seasonal
citrus N demand, water use, and N uptake is needed to minimize water use and nitrate
leaching in citrus management. The objectives of this study were to 1) determine long-
term and seasonal changes in citrus biomass and N distribution, 2) develop spatial
patterns of citrus root length density with increase in tree size, 3) estimate crop water use
and soil moisture coefficients, and root water uptake efficiency, and 4) explore seasonal
N uptake rates for citrus. Total tree biomass and N distribution were related to canopy
volume and trunk cross sectional area. The percentage of total tree N in citrus leaves
decreased from 45 to 37% while branch N increased from 6 to 27% as tree canopy
volume increased from 5 to 35 m^3. Leaf, branch, and root masses comprised 15, 65, and

20% of total mature tree mass, and accounted for 45, 35, and 20% of total N mass, respectively. Root density increased radially as tree size increased. Trees on Swingle citrumelo rootstock had a higher proportion of fibrous roots near the soil surface than trees on Carrizo citrange. Soil water uptake ranged from 0.8 to 1.1 of ET_o. Daily uptake decreased steadily as soil water content decreased. N uptake from the upper 45 cm of soil was greater for trees on Swingle citrumelo compared with Carrizo citrange. N uptake efficiency ranged from 41 to 55% when fertilized at 269 kg N ha^{-1} compared with 47 to 70% when fertilized at 179 kg N ha^{-1}. Leaf and twig N was highest from August to February and lowest in May. New and improved understanding of citrus water and N dynamics will advance Florida citrus management techniques and decrease environmental impacts.

CHAPTER 1
INTRODUCTION

With a crop value of $640 million in 2002, citrus is one of the most important horticultural crops in Florida. Currently, nearly 2 million ha are under citrus production, with a 1.1 million metric ton annual production accounting for 73 and 18% of US and world production, respectively (Florida Agricultural Statistics Service, 2002). Citrus is typically produced on sandy soils with poor water and nutrient retention capacity. Adequate supply of both irrigation water and fertilizer are therefore required for optimal production. Most ridge soils lack confining soil layers that can prevent fertilizer nitrates from reaching groundwater. Two issues have become greater concerns for citrus production in Florida: 1) increasing competition between agricultural, commercial, and residential use of limited water supplies, and 2) nitrate contamination of some aquifers less than 50 m deep.

Fertilizer application rates and irrigation management practices for citrus rely upon crude general recommendations that are standardized over large areas and lack the precision needed in today's ecologically conscious and competitive markets. Although fertilizer and irrigation recommendations provide general production guidelines, they do not capture the dynamic nature of processes controlling non-point source pollution associated with citrus production. Therefore, both growers and regulators must be provided with additional tools such as decision support systems to improve water and

1

nutrient use efficiencies and assessment of Best Management Practices (BMP) impacts on citrus production and ground water quality.

Ridge Water Quality Study

The U.S. Environmental Protection Agency, in a nation-wide survey, documented widespread nitrate contamination of shallow drinking water wells (Graham and Alva, 1995). In that survey, approximately 55% of wells were found to contain NO_3-N contamination above the background concentration. Approximately 1.2% and 2.4% of urban and rural drinking water wells, respectively, were found to contain NO_3-N concentrations above the Maximum Contamination Level (MCL) of 10 mg L^{-1} for drinking water. A correlation between drinking water well contamination and areas with higher fertilizer sales and high value crops was established (Graham and Alva, 1995) suggesting that agricultural fertilization practices may have contributed significantly to NO_3-N contamination of drinking water wells.

Of 3949 drinking water wells surveyed by the Florida Department of Agriculture and Consumer Services (FDACS), 2483 (63%) contained detectible concentrations of NO_3-N (Graham and Wheaton, 2000). Of these 2483 contaminated wells, 584 (15% of total surveyed) contained NO_3-N in excess of MCL. The proportion of wells in Florida contaminated with NO_3-N was similar to that of the nation-wide survey. However, the proportion of wells contaminated above MCL was an order of magnitude higher, suggesting that the soils of the state of Florida on average are vulnerable to NO_3-N leaching to groundwater. Eighty-nine percent of wells contaminated above MCL were located in the central Florida counties of Lake, Polk, and Highlands (Fig. 1-1). Portions of these three counties comprise the central Florida ridge. Soils typical of the "ridge" are

hyperthermic Entisols composed of uncoated sands with water holding capacities of 0.04 to 0.09 cm^3 cm^{-3}, hydraulic conductivities >50 cm h^{-1}, cation exchange capacities of 1 to 5 cmol (+) kg^{-1}, and depths of more that 10 m.

Long-term monitoring studies and research projects were initiated in 1992 to evaluate the impacts of nutrient and water management practices in citrus on ground water quality. The goals of the projects established by FDACS (Graham and Alva, 1995) were to 1) generate baseline groundwater quality data from several commercial citrus groves in the ridge area; 2) develop recommendations for alternative nutrient and water management practices; and 3) assess the impacts of these alternative management practices on groundwater quality.
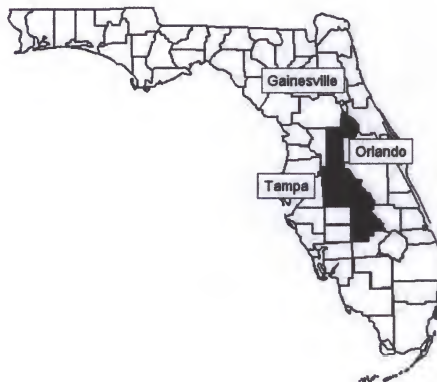
Fig. 1-1. Map of Florida with Lake, Polk, and Highlands counties highlighted.

Results of this study indicated that N removed at harvest accounted for only 30 to 49% of the applied N (Alva and Paramasivam, 1998). Estimates of N added to the biomass of the trees ranged from 18 to 57% of the N applied. The study concluded that additional information was needed for N accumulation with increase in tree size, optimal timing for N application, N uptake parameters, and improved irrigation scheduling (Graham and Wheaton, 2000).

Citrus Best Management Practices

A best management practice (BMP) for any agricultural commodity is an attempt to use the latest scientific data available to reduce the impact of agricultural operations on the environment while maintaining economically viable production. An interim BMP for citrus was established in 1994 that was based on previous N rate studies and current IFAS recommendations. Citrus growers agreeing to abide by the interim BMP would not be held liable by the Florida Department of Environmental Protection for future cost of supplying drinking water to local users as required by Chapter 376.30 (3) (c) F.S. (Graham and Alva, 1995).

The terms of the interim BMP for orange trees 4 years or more of age were quite broad. Annual N applications were restricted to 134 to 269 kg ha^{-1} with the stipulation that groves producing less than 50.4 Mg of fruit per ha should apply no more than 202 kg ha^{-1} N annually. A minimum of two applications per year were required for bearing groves receiving up to 168 kg ha^{-1} N. Bearing groves receiving more than 168 kg ha^{-1} N per year were required to receive at least three applications. Those groves using fertigation were required to make a minimum of 10 applications. Application of at least half of the annual fertilizer N prior to the rainy season was encouraged. A UF-IFAS

publication (Tucker et al., 1995) was produced to assist growers in determining the rate of N to apply, timing of application, and suggested irrigation scheduling.

In 2002, a revised BMP established rates and timing of N applications based on tree age classes and method of application. The two age classes are 4 to 7 years and >7 years. The methods of application are broadcast only, broadcast and fertigation, and fertigation only. No more than 34 kg ha^{-1} N is to be applied at one time, and no more than 34 kg ha^{-1} N may be applied from June 15th to September 15th. No fertigation application is to exceed 17 kg ha^{-1} N and must be applied at a minimum 1-wk interval.

Decision Support Systems

Important decisions for growers are when and how much fertilizer and irrigation to apply. They need to consider several factors in their decision-making process to determine that the crop value to be gained is greater than the cost of fertilizer and irrigation applied. Fixed fertilizer and irrigation schedules, based on long-term mean climatic conditions, may lead to inefficient use of these inputs due to the large annual variability in atmospheric conditions (Heinemann et al., 2000). Likewise, variations in the amount of rainfall and its distribution may lead to the loss of N from the crop root zone necessitating additional applications. Due to the complexity of the decision making process, researchers have developed computer-based decision support systems (DSS). A DSS can provide information on management options based on local environmental conditions. These systems also provide a means to make the scientific understanding of complex plant, soil, and environmental interactions accessible to decision makers in a concise and interactive manner. Frequently, information from simulation models has formed the foundation for these DSS.

Nutrients leached from agricultural soils represent both an economic loss to farmers and a potential environmental pollutant for groundwater. Concerns about the presence of these agricultural chemicals in groundwater and the need for improved understanding of their movement and transport beyond the root zone have increased considerably over the last several decades. Comprehensive mathematical relationships are required to determine crop fertilizer N uptake and to predict the potential impact of NO_3-N leaching on groundwater quality for various soil and/or environmental conditions. With the exception of insect and disease population and damage dynamics, most modeling work has focused on predicting mineral N transformations, organic C and N transformations, soil water content, water and N uptake, crop yield, and NO_3-N leaching (Hoogenboom et al., 1994). Such models help growers manage resources, maximize returns, and reduce impacts on water quality. Current crop simulation models are being used to optimize planting dates and densities (Saseendran et al., 1998), optimize fertilizer and irrigation inputs (Sexon et al., 1998, and Heinemann et al., 2000), maximize profits (Kiniry et al., 1997), and reduce groundwater pollution (Gijsman et al., 2002) in agronomic crops.

Objectives

Robust crop models can provide a scientific basis for improved resource management in agricultural production. The long-term accumulation of biomass and N with tree development must be understood. Figure 1-2 illustrates the relationships between tree biomass, tree N content, soil N concentration, and soil water content. Change in tree biomass and N content over time impacts total tree N demand. Soil N and water concentrations affect both active and passive N uptake rates. Likewise, changes
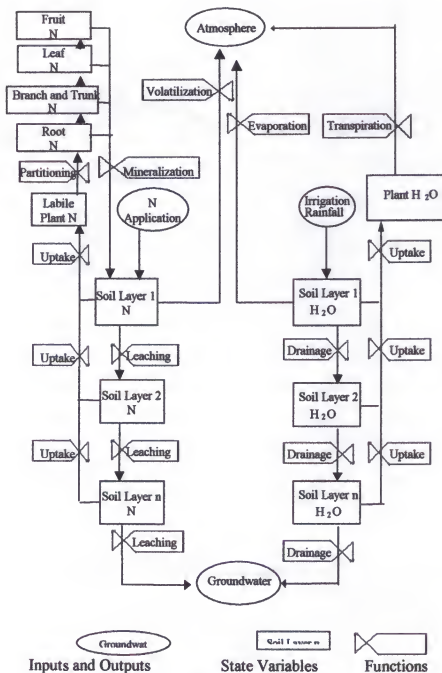
Fig. 1-2. Plant/soil nitrogen and water balance flow chart.

in root distribution with time must be known to understand the effect of these distributions on the rate of water and nutrient uptake and thus soil water and N concentration. An additional complication is that citrus tree scions are grafted onto rootstocks that affect the growth and uptake rates of the resulting tree. The effects of these rootstocks on tree development and uptake rates must also be understood.

To develop a crop model for citrus, detailed field-scale information must be obtained under local soil and cultural conditions. A review of the existing literature for these relationships was conducted. The result of this review will be presented in Chapter 2. Information gaps in biomass and N accumulation and field-scale uptake rates of mature citrus trees must be determined so that studies can be designed to complement existing information. The central hypotheses tested in this dissertation are 1) generic relationships can be developed that capture changes in citrus dry biomass, N weight, and root length densities with increase in tree size; 2) daily water uptake changes seasonally and is greatly affected by soil water content; 3) seasonal leaf N concentration is lowest and tree biomass abscission is highest during periods of rapid tree growth; and 4) fertilizer-N nitrification and uptake are rapid under Florida conditions. Therefore, the objectives of studies in Chapters 3-6 were to 1) determine changes in above-ground citrus biomass and N distribution for trees under recommended N fertilizer management practices across a range of tree sizes; 2) develop relationships that will capture the overall spatial patterns in citrus root length density distribution for different tree sizes; 3) estimate irrigation crop and soil moisture coefficients and soil water use per unit root length density; 4) explore seasonal N uptake rates for citrus; and 5) compare seasonal biomass and N concentration changes for citrus fertigated at two N fertilizer rates.

CHAPTER 2
LITERATURE REVIEW

Introduction

The various species of the genus Citrus are believed to be native to the subtropical and tropical regions of Asia and the Malay Archipelago (Webber and Batchelor, 1943). Citrons were cultivated on the European continent as early as 300 BC. Limon and sweet orange were not known in Europe for some 15 and 17 centuries later, respectively. Sweet orange was first introduced to the North American continent on Columbus' second voyage in 1493. Citrus was grown in coastal settlements of Florida by the mid 16th century and "wild" citrus trees were found on hammocks near lakes or rivers where conditions were particularly favorable for their growth in the second half of the 19th century (Harris, 1875; Adams,1875). Due to freeze damage, citrus production in Florida has moved in the last 120 years from north central Florida to the southern half of the Florida peninsula. Currently 2 million ha of citrus fruit are grown in Florida (Florida Agricultural Statistics Service, 2002). Florida citrus production was 1.1 million metric tons accounting for 73 and 18% of US and world production, respectively.

Vaile (1924) showed that fine sand or sandy loam soils resulted in better growth and production than coarse sands or heavy loams. Subtropical in nature, citrus trees do not exhibit dormancy or shed their leaves during the winter months However, new growth appears in definite cycles, with two to four cycles of growth yearly. The first and usually largest growth starts in the early spring (late February to early March), the second

9

from early June to early July, and the third in late summer (August or September). The principal blooming period for all commercial species is early spring and usually lasts approximately 6 weeks (Mid February to late March). The normal period of ripening of most citrus fruits is late fall and winter, preceding the spring bloom. However, late maturing varieties such as 'Valencia' require 12 to 15 months for maturity, which occurs after bloom for the next crop. The period of time when citrus fruit can be harvested is about 9 months.

Citrus production areas in Florida range from upland positions with very sandy "Ridge soils", which are deep and excessively well drained, to relatively low "flatwood" sites that are often flooded in their native state due to the presence of a spodic layer. Flatwoods soils must be drained and bedded before planting to lower the fluctuating water table. Each of these general areas in Florida presents somewhat different challenges for growing citrus trees and fruit production. Although crop growth and nitrogen uptake dynamics are readily available for many agronomic crops, this information is in short supply for citrus. A comprehensive literature review relevant to citrus growth characteristics, root distribution, water and N uptake dynamics, and crop growth models will be presented in this chapter.

Citrus Growth Characteristics

Turrell et al. (1969) proposed citrus tree growth equations based on growing conditions and cultural practices in California. These equations assumed citrus tree growth to be logistic in nature depending on cultural characteristics such as spacing, pruning, and irrigation and fertilizer scheduling, soil characteristics, and climatic conditions. Several studies measuring citrus biomass in relation to nutrient concentration

distribution or uptake have been conducted, but few biomass studies have been conducted

for a range of tree sizes grown under similar cultural soil and climatic conditions.

Citrus Biomass Distribution

Legaz and Primo-Millo (1981) harvested 4 year-old 'Valencia' orange trees

grown outdoors in sand culture in Spain at five different times in a 1-year period. The

mean dry mass percentages for leaves, twigs and branches, lateral roots and fibrous roots

were 22.5, 28.7, 45.8, and 2.9% respectively.

Cameron and Compton (1945) divided eight year old 'Valencia' trees grown in

California into 14 parts, 1) leaves, 2) twigs, 3) shoots, 4) lateral branches 0.75-1.5 cm, 5)

tertiary branches 1.5-3.0 cm, 6) secondary branches 3.0-6.0 cm, 7) primary branches >

6.0 cm, 8) trunk, 9) main root, 10) feeder roots, 11) rootlets, 12) small roots 0.3-0.8 cm,

13) intermediate roots 0.8-2.5 cm, and 14) large roots > 2.5 cm. The difference between

twigs and shoot was not given, but both had similar N concentrations on a dry mass basis

(5.11 and 5.02%, respectively). Likewise, the sizes of rootlets and feeder roots were not

given but had similar total N percentages (1.38 and 1.49%, respectively). Mean

percentage dry weight of leaves, twigs and shoots, branches, trunk, main root, lateral

roots and fibrous roots were 16.8, 9.6, 43.2, 1.5, 2.1, 14.0, and 1.7% respectively.

The biomass proportions for young 'Hamlin' orange trees grown under Florida

conditions were substantially different. In a study by Mattos (2000), eight categories of

plant parts for 7 year-old 'Hamlin' orange trees were used. These categories were 1)

summer-fall flush leaves, 2) spring and older leaves, 3) twigs >1.5 cm, 4) twigs <1.5 cm,

5) trunk, 6) roots <0.2 cm, 7) roots 0.2 to 1.0 cm, and 8) roots >1.0 cm. Leaves, branches,

trunk, lateral roots, and fibrous roots constituted 13.9, 37.4, 9.0, 10.2 and 14.2% of total dry biomass, respectively.

In a ^{15}N study, Feigenbaum et al. (1987) divided 22 year-old Shamouti orange trees fertilized at two annual N rates into seven components: 1) leaves, 2) twigs <5 mm, 3) branches >5 mm, 4) trunk and main branches, 5) main root (tap), 6) lateral roots >1 mm, and 7) fibrous roots <1 mm. There was no diameter given to differentiate between branches and main branches. Biomass percentages for leaves were 6.4 and 8.4% for the low and high N treatments respectively. Similar differences were found for all categories with the exceptions of main and lateral roots. The ranges in mean percentage of fresh biomass for twigs, branches, trunk and main branches, lateral roots, and fibrous roots were 1.6 to 2.2, 32.5 to 33.4, 24.5 to 29.2, 4.6 to 6.1, and 3.8 to 4.8%, respectively. These differences between fertilizer-N rates resulted in a greater percentage of biomass below ground for the low nitrogen application (34.1%) compared with that of the higher nitrogen rate (27.8%).

In a similar study, Kato et al. (1984) found different values for 21 year-old Satsuma mandarin trees in Japan. In this study, mean percentages of dry biomass for leaves, twigs, branches, trunk, lateral roots and fibrous roots were 15.7, 4.7, 32.2, 23.1, 20.3, and 3.1% respectively.

Citrus Nitrogen Accumulation and Partitioning

Nitrogen balance studies in citrus provide information on physiological tree N requirements and can be used to develop methods that minimize potential losses of N to groundwater and the atmosphere (Feigenbaum et al. 1987). In a study of 8 year-old 'Valencia' trees in California conducted during a period of 2 years (Cameron and

Compton, 1945), leaves contained from 40 to 50% of total tree N. Twigs and shoots contained approximately 10% of total N. Trunk and branches contained from 20 to 30% of total tree N. Approximately half of this N was in the bark, whereas this tissue component represented only 5% of the total dry mass. Roots contained from 15 to 20% of the N, half or more of which was in the bark that made up only 5% of the dry mass of the tree.

Seasonal changes in leaves, bark, twig, and root N concentration were greater than N changes in woody branch tissue. The trees contained more N just before initiation of growth activity during spring than at any other time of year. Maximum bark N content occurred about December 1, followed by a decrease. It was speculated that the reduction between December and February was the result of deposition of starch and possible other carbohydrates in these tissues. A decrease of all tree tissue N concentration occurred during bloom, fruit set, and periods of active growth in the spring and early summer. During the summer and autumn, N concentrations gradually increased to the mid-winter maximum. Mattos (2000) found similar N concentration values for 7 year-old 'Hamlin' trees. Nitrogen concentration was lowest in the trunk and taproot of these trees. The N concentration of leaves (2.1 to 2.6%), twigs (0.4 to 0.8%), and roots (0.6 to 1.7%) varied with tissue age. Younger tissue tended to have greater N concentration compared with older tissues.

Citrus Root Growth Dynamics

Citrus trees are productive and grow well on central Florida deep sandy soils. In some instances, tree size and yield appear to be related to root system characteristics (Castle and Krezdorn, 1975). Citrus fibrous roots are commonly defined as those roots <4

mm in diameter. Their dry mass is a relatively small part of the total root system, but their composite length far exceeds that of the woody roots (>4 mm in diameter). These fine roots are considered to be the "functional" part of the root system because of their critical role in water and nutrient uptake. There is some variation among rootstocks in the morphology of fibrous roots (Castle and Youtsey, 1977). Some rootstocks like trifoliate orange *[Poncirus trifoliata* (L.) Raf.] produce higher specific root length or length/unit mass (Eissenstat, 1991). Fibrous roots are also the most vulnerable part of the root system. Their development, function, and longevity are strongly influenced by soil characteristics, environmental changes, crop species, crop growth stage, and cultural practices.

Factors Affecting Root Distribution and Root Density

Soil Characteristics

The distribution of roots is modified by the physical and chemical properties of the soil profile (Hillel, 1971). Widespread root development and high fibrous root concentrations were observed in deep soils of sand texture where there were virtually no impediments to root growth provided that water and nutrients were non-limiting to growth (Ford 1952; 1953a&b; 1954a&b; 1959; 1964; 1972); Ford et al., (1954; 1957). Increased tree size and yield have been related to root system depth and fibrous root mass. The depth of rooting of 'Orlando' tangelo trees on 10 rootstocks growing in deep, sandy soil was correlated with tree height (Castle and Krezdorn, 1975). Although fibrous root distribution was affected by tree height, total fibrous root dry mass measured at the canopy dripline was not correlated with tree height. Ford (1954a; 1964; 1968; 1969; 1972) conducted many studies of citrus trees in poorly drained Spodosols of Florida and

concluded that tree size was closely related to fibrous root density. Extensive lateral root development occurred on soils with loamy or clay texture (Boswell et al. 1975; Kaufimann et al., 1972). In these studies, the root systems were shallower than root systems of plants grown in sandy soils with few roots found below a soil depth of 50 to 70 cm (Adriance and Hampton, 1949; Boswell et al., 1975, Cahoon et al., 1956; 1959; 1961; Kimball et al., 1950; Mikhail and El-Zeflawi, 1978). Furthermore, changes in fibrous root distribution with depth were more gradual compared with sandy soils, and overall fibrous root concentrations were lower (Bielorai, 1977). The lower natural soil fertility (Carlisle et al., 1989), and excessive drainage of sandy soils resulted in higher shoot:root ratios such that fibrous root dry mass densities tended to be lower in sandy soils (Castle, 1978).

Under flatwood conditions where the soil is drained and bedded, virtually all the root mass occurs within 45 cm of the soil surface (Calvert et al., 1967; 1977; Ford, 1954a; Ford, 1972; Reitz and Long, 1955). The quantity of fibrous roots decreases with depth and lateral distance from the trunk. Elezaby (1989) reported lateral fibrous root distribution to a depth of 180 cm of a 10-year-old 'Valencia' tree *[Citrus sinensis* (L.) Osb.] on 'Volkamer' lemon *(C. volkameriana* Ten. and Pasq.) grown on a soil with a deep sand profile and spaced at 4.5 m x 6.0 m as: 9% of the fibrous roots between 0 cm and 60 cm from the trunk, 31% between 120 cm and 180 cm, and 21% between 240 cm and 300 cm. The vertical distribution was: 42% of the fibrous roots between 0 cm and 30 cm from the soil surface, and 14% or less at each 30-cm depth increment to 180 cm. In the same study, fibrous root dry mass density (concentration) ranged from 300 g m^3 to 1200 g m^3. Those data are similar to dry mass densities reported in other Florida studies

(Castle, 1978; 1980). In a recent report, data were given as root length densities and ranged from 530 cm m^{-3} for 'Swingle' citrumelo roots *[C. paradisi* Macf. x *P. trifoliata* (L.) Raf]* to 2020 cm m^{-3} for trifoliate orange (Eissenstat, 1991).

Climatic Effects

Root distribution was studied in 22 mature navel or 'Valencia' orange groves in California (Cahoon et al., 1956). In this study, 50% were low-yielding while the remaining 50% were high-producing. Fibrous root fresh mass was measured to a depth of 90 cm under the canopy and between rows. Yield was not related to the under-canopy root quantities, but was correlated with the root quantities measured between adjacent rows where soil water contents were typically lower most of the year.

Rootstocks

Some citrus roots have been found as deep as 7 m (Ford, 1954b*)*, and in one instance, roots of mature trees on rough lemon rootstock were discovered 14 m from the tree trunk (Ford, 1970). Castle and Krezdorn (1975) described two general types of root systems, the first characterized as "extensive" featuring extensive lateral and vertical development, and the second as "intensive" with less extensive root expansion and higher fibrous root concentrations mainly confined to the upper soil layers. Trees on rough lemon, 'Volkamer' lemon and 'Palestine' sweet lime (*C. limettioides* Tan.) rootstocks typified the extensive type of root system where 50% of the fibrous roots occurred below 70 cm in the soil with wider spreading lateral development. Examples of the intensive type were 'Rusk' citrange and trifoliate orange, where few fibrous roots were found below 70 cm, and the root system was less developed laterally. Some rootstocks like sour orange and 'Cleopatra' mandarin were classified as intermediate. Trees on 'Cleopatra'

mandarin had a highly developed lateral root system at the surface, but few fibrous roots below the surface. Menocal-Barberena (2000) found no statistically significant differences in vertical or horizontal fibrous root distribution of 'Hamlin' orange on 'Cleopatra' mandarin, 'Swingle' citrumelo and 'Carrizo' citrange rootstocks. Vertical and horizontal root distribution were similar to other studies with about 40% of the fibrous roots in the top 30 cm and 9 to 14% at each of the remaining 30 cm depth increments to 180 cm. Few roots were found below 180 cm.

Tree Spacing and Density

Due to Florida's rainy season, roots of trees at commercial spacing rapidly occupy the volume of soil outside the irrigated zone. After canopy closure, they extend into the rootzone of adjacent trees. Elezaby (1989) reported fibrous root concentration in the 0 to 30 cm zone increased from 450 to 1000 g m^{-3} between trees when the in-row distance decreased from 4.5 to 2.5 m. The increased root concentrations in this study were concluded to be the result of overlapping root systems. Trees at the closest spacing showed root concentration increases to depths of 150 cm (Elezaby, 1989).

Fertilization

Increases in fertilizer N can increase root growth to a considerable depth, but the largest effects generally occurred near the surface (Ford, 1953b; Ford et al., 1957; Smith, 1956; Smith, 1965).

Irrigation

Irrigation method and scheduling has been shown to change the distribution and/or concentration of citrus fibrous roots. In a California study of trees receiving different irrigation treatments, yield was not correlated with fibrous root density (Cahoon

et al., 1964) because trees in the low irrigation rate treatment declined in yield while maintaining root quantities similar to those of the trees in the higher irrigation rate treatment. It was concluded that soil water content was the single most important factor influencing citrus root systems.

In a Florida study, root weight densities were determined under the tree canopy, at the dripline, and in the row middles to a depth of 180 cm for 'Hamlin' orange trees on 'Swingle' citrumelo and 'Carrizo' citrange rootstocks (Menocal-Barberena, 2000). Trees receiving irrigation at a rate of 40 cm yr^{-1} had significantly higher densities than trees receiving 250 cm yr^{-1}. The differences were on the order of 1.3 to 2.3 times greater for the 40 cm yr^{-1} treatment at all depths.

Canopy Reduction

Hedging, the annual removal of excess vegetative growth, has become a common method of canopy size control for closely-planted citrus trees. Eissenstat and Duncan (1992) found that within 30 days of canopy reduction, 20% of the fibrous roots between the 9 cm and 35 cm depths were apparently dead. Root length density of these trees recovered within 63 days of canopy reduction. This relatively short-term reduction in fibrous root density adversely affected yield because of fruit abortion.

Citrus Water Uptake

Assuming little or no surface runoff, water applied to the soil surface is 1) retained in the soil, 2) utilized by plants, 3) lost to the atmosphere, or 4) drained below the crop rooting zone. Drainage water may contain substantial quantities of agricultural chemicals and soluble nutrients. Irrigation practices should be aimed at minimizing 1) crop water stress by maintaining sufficient water within the crop rooting zone, 2)

pollution of groundwater by leaching, and 3) production costs associated with excessive irrigation, and nutrient and pesticides losses due to leaching.

Mills et al. (1999) reported a significant decrease in citrus stomatal conductance after midday. This decrease was most pronounced for south-facing exterior leaves and increased with increasing evapotranspirational demand (ET_o). Soil water use from 2 year-old 'Hamlin' orange trees measured at 0.5-hour intervals using weighing lysimeters indicated that water continued to be removed several hours after the midday decrease in stomatal conductance. Two seemingly opposing theories place control of soil water uptake at the leaf level via leaf water potential (Slatery, 1967) or root via root water potential (Tinker and Nye, 2000). The former assumes that leaf water potential exerts control on stomatal conductance regulating transpiration and thus water uptake. The latter speculates that dehydrating roots, due to low soil water content, indirectly control stomatal conductance through the production of chemical compounds that after translocation to the leaves reduce stomatal aperture. Lafolie et al. (1991) measured decreasing leaf water potential with decreased root water potential until midday. After reduced stomatal conductance at midday, leaf water potential increased without a corresponding decrease in root water potential. This result was given as evidence that stomatal conductance was not controlled by leaf water potential alone.

Factors Effecting ET_c

Crop species

Citrus are evergreens and therefore require water for transpiration throughout the year. Citrus leaves are thick and waxy, resulting in high cuticular resistance to transpiration (Mills et al. 1999). Koo (1963) and Koo and Sites (1955) stated that water

requirements of grapefruit are generally higher than orange or mandarin varieties for trees

of equal size. Wiegand and Swanson (1982 a, b, c) and Wiegand et al. (1982) reported

that mean daily citrus ET_c at Weslaco, Texas ranged from 2.2 to 3.3 mm for Ruby Red

grapefruit and 1.9 to 2.7 mm for Marrs oranges from 5 to 10 years of age.

Under similar climatic conditions, citrus trees are known to have lower

transpiration rates compared with other crop plants. Mahrer and Rytwo (1991) reported

mean estimated daily crop water use (ET_c) rates for cotton in the Hula Valley of Israel of

5.4 mm when irrigated daily, and 4.0 mm during a 14-day period when not irrigated.

Likewise, Starr and Paltineanu (1998) reported that daily ET_c rate for full canopy corn at

Beltsville, MD ranged from 3.8 to 5.0 mm prior to rainfall and 5.2 to 8.0 mm after.

Lower citrus transpiration rates are related to lower leaf and canopy conductance (Mills

et al. 1999).

Tree size

Large, vigorous, healthy trees require more water than young trees (Tucker et al.

1997). In Florida, large trees at low planting densities (150 to 180 trees per ha) may use

62 to 94 L per day during the winter months and 189 to 219 L per day in July and August

(Boman, 1994). Rogers and Bartholic (1976) reported a mean annual ET_c of 1210 mm

during an 8-year period from a young orange and grapefruit grove on poorly drained soils

near the east coast of Florida. These annual ET_c values ranged from 820 mm early in the

study (tree age 2 years) to 1280 mm at end of the study (tree age 10 years). Linear

regressions of annual ET_c vs. years during the study resulted in significant (P=0.1)

increase in ET_c. Mean annual ET_c increased at a rate of 19 mm per year or a cumulative

increase of approximately 13% in 8 years. Fares and Alva (1999) reported an annual ET_c

value of 920 mm for 3-yr old 'Hamlin' orange trees grown on deep sandy soils in central Florida. Koo and Harrison (1965), and Koo and Hunter (1969) reported annual ET_c values of 1170 mm for mature citrus on the same soil series.

Climate

Mean annual ET_c for citrus in Florida ranges from 820 to 920 mm (Rogers and Bartholic 1976; Fares and Alva 1999) for young (<5 years) trees to 1170 to 1280 (Koo 1978, Rogers and Bartholic 1976) for mature (10 years or more) trees. Annual ET_c values reported for mature citrus grown in the lower Rio Grande Valley of Texas are similar to those for Florida and ranged from 1044 to 1232 mm (Wiegand et al. 1982). Hoffman et al. (1982) reported annual ET_c values for well-irrigated citrus grown in semi arid Arizona of 1470 mm. Lower ET_c rates for Florida (humid) compared with Arizona (semi-arid) have been attributed to lower evaporative demand (Rogers et al. 1983, Fares and Alva 1999).

Soil characteristics

Crop water supply must be based on a clear understanding of soil water dynamics. Water in excess of field capacity drains through the vadose zone. Eventually, water that is not taken up by plants or evaporated from soil or plant surfaces makes its way into the ground water and contributes to aquifer recharge (Fares and Alva, 1999). Under-tree sprinklers and drip irrigation systems are designed to deliver water at rates low enough to allow infiltration into the soil without contributing to losses by runoff. These systems can be managed in such a manner that the excessive downward drainage through the soil is minimized. The required application amount is governed by the soil-water depletion on a given irrigation date, irrigation efficiency, and the target soil-water level. Most of the

terms are not independent. For instance, the amount of applied irrigation water will influence the amount of ET_c as well as the amount of drainage (Prajamwong et al., 1997).

In standard irrigation practices, water transport through the soil may be classified into five phases: 1) infiltration during application; 2) redistribution after application ceases; 3) withdrawal by plant roots; 4) evaporation from the soil surface; and 5) drainage of water to lower soil depths. The primary modes of transport of water in soil are 1) viscous flow through liquid-filled pores, and 2) diffusion of vapor through air-filled pores. In principle, both modes contribute to soil water flow. Liquid flow is the dominant mode in saturated to moist soils (Hagan et al., 1967). Vapor flow is of minor importance until soils become quite dry, although the presence of a large temperature gradient favors the contribution of this mechanism. For typical soil water situations, both of these transport modes contribute to a flow rate proportional to potential energy gradients within the soil.

Water is of central importance in the transport of solutes in soils or plants, whether by diffusion or mass flow (Tinker and Nye, 2000). The concept of potential is fundamental to understanding soil water dynamics. Potential is a measure of the energy state of a chemical compound within a particular system, and hence of the ability of a unit amount of this compound to perform work. Difference in potential at different points in a system gives a measure of the tendency of the compound, including water, to move from a region with high potential to a region of lower potential.

Soil water has various forms of potential energy acting on it, all of which contribute to the total potential. Tinker and Nye (2000) refer to these forms of potential energy as concentration, compression, position in an electrical field, and position in the

gravitational field. These same forms of energy are commonly referred to as osmotic, matrix, gravitational and pressure potentials, the sum of which is referred to as total water potential (ϕ). Thus, soil water moves in response to the difference in water potential over a distance. The first published relationship between water flux and energy gradient was obtained empirically in 1856 by Henry Darcy after a study of saturated sand filters (Hagan et al., 1967).

$$\upsilon = -K \, d\phi / dx \qquad \qquad \text{Equation 2-1}$$

Where:

υ = water flux ($cm^3 \, cm^{-2} \, s^{-1}$),

K = hydraulic conductivity constant ($cm \, s^{-1}$),

ϕ = soil water potential (kPa), and

x = the distance over which the flux is maintained (cm).

The constant of proportionality of Darcy's Law (K) is known as the hydraulic conductivity, and is a function of both the properties of the medium and the fluid (Tindall and Kunkel, 1999). In saturated soils, K will be constant as long as the structure of the soil remains stable because the water flow pathways will be unchanged. In unsaturated soil, K varies with the water content (θ), because the latter defines the total cross-section area for water flow, the effective water-filled pore radius, and the effective pathlength (Tinker and Nye, 2000). A soil with a wide range of pore sizes conducts fluid more rapidly than a soil with small pore sizes (Tindall and Kunkel, 1999). The saturated hydraulic conductivity of soils has a wide range from $10^{-9} \, cm \, s^{-1}$ for clay to $1.0 \, cm \, s^{-1}$ or more for sand. Lower values of K for a clay medium (with smaller pore sizes) are likely due to the drag exerted on the viscous fluid by the walls of the pores. Particles of smaller-

sized individual grains (such as clays compared with sands) have a larger surface area that increases the drag on water molecules that flow through the soil, reducing permeability and hydraulic conductivity.

As water is lost from the soil, the continuity between water-filled pores also decreases. A soil with water-filled volume fractions less than 0.1 ($\theta < 0.1$ cm^3 cm^{-3}) will normally have a very low value for K(θ) (Tinker and Nye, 2000). The Poiseuille equation states that the flow rate in a tube increases proportionally to the fourth power of its radius, at a constant pressure gradient. Water in larger soil pores will empty first as the soil dries, effectively reducing the cross sectional diameter of the soil water pathway. Therefore, pore size and distribution has a large effect on the flow rate

$$f = (\pi\, r^4 / 8\eta)\, dP/dx \qquad\qquad \text{Equation 2-2}$$

Where:

f = flow rate in a tube (m^3 s^{-1}),

r = radius (m),

η = viscosity (μPa s^{-1}), and

dP/dx = pressure gradient.

The driving force for soil-water movement is the difference in matric potential, resulting from a difference in soil water content. Richards postulated that Darcy's Law could be extended to unsaturated states by assuming that the hydraulic conductivity (K), as well as the water content, could be treated as non-hysteretic functions of the pressure head or potential (Slatery, 1967). The matric potential and the water content for a soil are related by the soil-water characteristic curve. By using the slope of the soil characteristic curve ($d\phi/d\theta$), the following equation can be obtained based on Darcy's Law and is

known as Richard's equation (Tinker and Nye, 2000). In this equation, flow in unsaturated soil can is expressed in terms of the water content gradient and soil water diffusivity (D_θ).

$$\upsilon = -K_\theta \, d\phi/dx = -K_\theta \, (d\phi/d\theta) \, (d\theta/dx) = -D_\theta \, (d\theta/dx) \qquad \text{Equation 2-3}$$

Where:

υ = water flux (cm^3 cm^{-2} s^{-1}),

K_θ = hydraulic conductivity constant at θ (cm s^{-1}),

ϕ = soil water potential (kPa),

θ = soil water content (cm^3 cm^{-3});

$d\theta/d\phi$ = slope of the soil characteristic curve, and

x = the distance over which the flux is maintained (cm).

The term diffusivity (D_θ) is used because the form of equation is the same as that of Fick's law of diffusion (Tinker and Nye, 2000). Furthermore, D_θ is somewhat less convenient than K_θ under conditions of hysteresis because D_θ is discontinuous at each reversal of the direction of potential, while K is continuous and virtually hysteresis-free (Hagan et al., 1967). Experimentally, the effect of hysteresis on Richards' equation has usually been ignored by limiting the soil water potential change to either always drying, or always wetting.

"Field capacity" (θ_{fc}) describes the water content held in the soil after excess water has drained to drier soil layers by redistribution. This equilibrium can be determined in the field by measuring the soil water content as a function of time to determine the value of θ when $d\theta/dt$ approaches zero. Hillel (1971) noted that the rate at which $d\theta/dt$ approaches zero is dependent on θ_i and the depth to which the soil is being

wetted. The concept of field capacity is useful in the design of field management schemes for approximating the maximum amount of soil water storage. Field capacity can be used as an upper limit value of θ within each soil layer such that any water in excess of θ_{fc} quickly drains to the next deeper soil layer. The soil profile can be described as a vertical sequence of reservoirs with the overflow level for each reservoir corresponding to the value of θ_{fc} for that specific soil layer. During irrigation or rainfall the top reservoir flows over to fill the next lower reservoir until no excess water remains to flow into the next reservoir. With a judicious selection of the depth of each soil layer, this simple analog of the soil profile can be easily modeled.

Soil water content

Estimated annual ET_c for a deforested area on the Florida ridge reached 680 mm (Sumner, 1996). This ET rate was attributed to periods of low soil water content because the area was not irrigated. Rogers et al. (1983) reported that growth and fruit yield of citrus trees were greater during a 3-year period for treatments maintained at higher soil water content. During the same period of time, annual ET_c averaged 900 and 1210 mm for the lowest and highest soil water content treatments, respectively. Hoffman et al. (1982) reported annual ET_c values to be 200 to 500 mm higher than that found by Erie et al. (1965) in Arizona. The lower annual ET_c values reported by Erie et al. were attributed to infrequent irrigation resulting in dry soil surfaces and thus increased resistance to water diffusion to the atmosphere. Smajstrla et al. (1986) reported a reduction in growth and ET_c with increased available soil water depletion of 2-year-old 'Valencia' orange trees grown in drainage lysimeters. Available soil water depletion setpoints used for irrigation scheduling in this study were 28, 47 and 58%. It was concluded that tree stress

occurred at the highest depletion value due to the reduced ability of the soil to transport water to the roots because of reduction in hydraulic conductivity. Fares and Alva (1999) calculated daily ET_c for 3-year-old 'Hamlin' orange trees on deep sandy soil in central Florida. Estimated daily ET_c values decreased with time after each rainfall or irrigation.

Water table depth

Obreza and Admire (1985) concluded that shallow water tables in flatwoods soils could significantly augment water available for root uptake. Graser and Allen (1987) suggested that water-table management by controlling water table depth in the winter and spring could help decrease the need for supplemental irrigation during the dry season. Boman (1994) used drainage lysimeters in which he maintained a water table at 0.61, 0.76, and 0.91 m to measure the effects of water table on ET_c, growth, yield and fruit quality of 5-year-old 'Valencia' trees. However, treatment effects were not significant.

Soil shading

Castel et al. (1987) estimated soil surface evaporation by comparing water loss from weighing lysimeters in which the soil was covered by plastic with lysimeters that remained uncovered. Mean estimated evaporation was reported as 0.78 mm, greater than 18% of the estimated potential ET of 4.25 mm. Castel and Buj (1992) reported that the percentage of ground shaded by young Clementine trees increased from 10 to 25% during a 4-year period. Evapotranspiration increased by 33% during the same time period. This increase was attributed to the increasing water use by the trees and reduced soil surface evaporation.

Grass and weed growth

Smajstrla et al. (1986) used field drainage lysimeters to determine the effect of grass cover on the growth and ET_c of 2-year-old 'Valencia' orange trees. Automated covers were installed to cover the lysimeters during rainfall. Soil within the lysimeters was maintained bare or covered completely with bahiagrass. The bare soil lysimeters consistently had the lowest monthly ET_c. Measured annual ET_c ranged between 1331 to 900 mm for grass-covered lysimeters and 912 to 441 mm for those with bare soil surfaces. Total ET_c was 46 to 105% higher per year due to soil grass cover. These results were similar to those reported by Stewart et al. (1969) using non-weighing lysimeters. In their study, estimated annual bare soil evaporation and 2/3 sod cover ET_c averaged 68 and 92% of full sod cover, respectively. Tucker et al. (1997) reported reduced soil water use from non-irrigated middles between rows of mature citrus by limiting the height of weed growth by chemical mowing.

Crop Coefficient

An estimate of evapotranspiration for a specific crop (ET_c) is calculated by multiplying the reference evapotranspiration (ET_o) by an empirically determined crop coefficient (K_c). This coefficient is specific for a crop, growth stage, and growing conditions. The resulting ET_c estimates water use of a crop under local or regional climatic conditions.

Rogers et al. (1983) reported monthly measured ET_c to calculated ET_o ratio values using the mean of four methods of estimating ET_o (Penman, Blaney-Criddle, Jensen-Haise, and Class A pan). The resulting monthly ratios range from 0.90 in January to 1.11 in June. Crop coefficient (K_c) values reported by Doorenbos and Pruitt (1977) after

adjustments for humid conditions ranged from 0.9 in March though December to 0.95 in January and February. Castel et al. (1987) estimated monthly K_c for drip-irrigated mature 'Navel' oranges grown in 'Valencia', Spain. Their K_c values were calculated from mean daily ET_c estimated from weekly ET values determined by neutron probe measurements. Values ranged from a mean of 0.71 from January through July to 0.90 from August through December. Castel and Buj (1992) suggested these values differed from those reported for Florida due to the lower evaporative demand of the humid Eastern coast of Spain, which has a mean annual ET_o of 1166 mm compared with 1400 mm in Florida.

Calculated K_c values for 3-year-old 'Hamlin' trees grown on sandy soil in central Florida ranged from approximately 1.05 in November through March to 0.85 in May through August (Fares and Alva 1999). Boman (1994) calculated K_c values for 5-year-old 'Valencia' orange trees grown in non-weighing lysimeters with water tables maintained at 0.6, 0.75, or 0.9 m from the soil surface. Calculated K_c values were at a minimum of 0.6 from December through February and peaked at 1.1 in June and July. Martin et al. (1997) estimated mean daily ET_c values for 7-year-old "Redblush" grapefruit in Arizona from soil water content data collected at 1 to 2 week intervals. Monthly K_c values were calculated by comparing these estimated daily values with mean daily ET_o for the same period. The resulting K_c ranged from a low of 0.55 to 0.6 in December and January to a high of 1.1 to 1.2 in July.

Soil Water Depletion Coefficient

According to Allen et al. (1998), the water depletion coefficient is defined as the effect of soil water reduction on ET_c by reducing the value of K_c. It is calculated by

multiplying the K_c of a given crop by the soil water depletion coefficient (K_s) for a given soil water content. Water stress increases as soil water is extracted by evapotranspiration.

Available soil water (ASW) is defined as the difference between drained upper limit (field capacity) and drained lower limit or permanent wilting point. However, the energy expenditure required to extract residual soil water increases as soil water content decreases. Likewise, resistance to water flow increases as residual soil water decreases, reducing water flux to the root boundary. Therefore, crop water uptake is reduced well before wilting point is reached (Allen et al 1998). At field capacity, roots can absorb water fast enough to supply the ET_c demand of the atmosphere. However, water becomes more strongly bound to the soil matrix and is more difficult to extract as soil water content decreases. When soil water content drops below a threshold value, water can no longer be transported quickly enough to the roots to supply the transpiration demand of the crop. The fraction of ASW above this threshold is known as readily available water (RAW). For most crops grown on medium and fine textured soils, RAW is as much as 30 to 50% of ASW (Allen et al. 1998). When root zone depletion exceeds this threshold, ET is reduced relative to potential crop ET_c and water stress occurs.

Citrus Nitrogen Uptake

Knowledge of the nutritional need of different plant organs as well as the seasonal demand for nutrients is essential in order to establish a physiological basis for crop fertilization (Lagaz and Primo-Millo, 1981). The potential contribution of fertilizer N to the deterioration of ground water quality may be appreciable (Embleton et al., 1978). This impact is especially true in Florida where the combination of high annual rainfall, sandy soils and shallow water tables create conditions that greatly increase the potential

for ground water contamination (Alva and Paramasivam, 1999; Calvert and Phung, 1972; Mansell et al., 1980).

Seasonal Nitrogen Uptake

Most N balance studies have been unable to completely account for total N applied to the soil. Some authors attributed this fraction (usually 30 to 50%) to atmospheric loss. Khalaf and Koo (1983) concluded that unaccounted for N was either incorporated into soil organic matter or stored in the tree (Dasberg, 1987), while others made no attempt to fully account for the applied N (Mansell et al., 1980).

Hilgeman (1941) estimated N uptake by grapefruit in Arizona by determining changes in leaf N concentration seasonally. Maximum N uptake by the trees occurred in March and September relative to January due to higher mean soil temperature. In a 3-year study, Chapman and Parker (1942) determined N removed from solution culture and reported that the months of least N absorption were January and February. Uptake rates increased during the period of late spring through early fall (May to October) with a maximum in July. Roy and Gardner (1946) in Florida reported similar results.

Numerous reports suggest that actively growing tissues act as a sink for N uptake and that the young developing leaves and fruit constitute the strongest sink. Legaz et al. (1982) in Spain studied N distribution in 5-year-old 'Calamondin' trees in sand culture. Trees were labeled with ^{15}N for 20 days during flowering, were harvested, and analyzed for N content 0 to 70 days later. Accumulated N was found primarily in fruitlets and newly developed leaves and twigs. About 30% of the labeled N was found in newly formed leaves. In Israel, Feigenbaum et al. (1987) treated 22-year old 'Shamouti' orange trees with ^{15}N labeled fertilizer. Trees had previously been supplied with sufficient N or

had been N-depleted to explore the influence of prior fertilization practices on subsequent N uptake. The highest percentage of labeled N occurred in fruit, new leaves and twigs. Only about 20% of the leaf and fruit N originated from the labeled source, suggesting considerable redistribution from stored reserves. Less than 14% of the labeled N was found in roots or large limbs. Dasberg (1987) found that 80% of the N in new growth came from stored rather than applied N, suggesting previous nutrition has significant influence on current season growth and fruit yield. Legaz and Primo-Millo (1988) reported increased N uptake from the beginning of spring flush to bloom. Uptake increased through the spring, reaching a maximum at the summer flush after which uptake declined gradually through winter.

Mooney and Richardson (1992) observed an N concentration gradient between the roots, trunk and branches of citrus trees in New Zealand. High concentrations were found in the branches, with lower concentrations in the roots. Nitrogen concentrations in the trunk were highest at bud break and declined steadily through fruit set and development to a minimum at fruit harvest. Nitrogen concentration for all categories peaked at flowering and then decreased steadily until harvest. Nitrogen uptake efficiencies of 82.0 and 74.1% for ammonium nitrate and urea, respectively, were reported by Mattos (2000). Legaz et al. (1982) reported 50 to 60% of total tree ^{15}N recovery in above-ground tree parts. Absorption rates increased only slightly from the beginning of growth until flowering, and increased sharply reaching a maximum value at the second growth flush (July) before declining during the fall and winter months. Dasberg (1987) demonstrated that the highest rate of ^{15}N uptake by citrus trees occurred during fruit set and the lowest occurred during winter.

Nitrogen Uptake Efficiency

Nitrogen uptake efficiency (NUE) is defined as the percentage of applied N taken up by plants (Scholberg et al. 2002). The ability of crop plants to take up and utilize N efficiently is key to providing adequate N for crop growth while reducing N leaching. Mattos (2000) estimated NUE for 6-year old 'Valencia' trees grown in a sandy soil to be 40% and 26% for ammonium nitrate and urea respectively. Feigenbaum et al. (1987) reported that the NUE for a ^{15}N labeled KNO_3 applied to 22 year-old 'Shamouti' orange was 40%. Syvertsen and Smith (1996) estimated NUE to be 61% to 83% for 4-year old grapefruit trees grown in lysimeters. Nitrogen uptake efficiency decreased with increased N application rates. Lea-Cox and Syvertsen (1996) reported a similar finding of lower NUE with higher N application rate for greenhouse grown seedlings. The NUE reported ranged from 47% to 60% after an uptake period of 31 days.

Kato et al. (1982) found a 10-fold increase in ^{15}N uptake of 'Satsuma' mandarin during summer (mean temperature 23 C) compared with the winter season (mean minimum temperature 3 C). Scholberg et al. (2002) found N uptake of greenhouse-grown seedlings to be proportional to soil temperature, ET_o and canopy biomass. Nitrogen uptake also increased with the time high N concentrations were maintained in the root zone. Increasing the residence time from 2 to 8 hours resulted in an increase in NUE of 95% and 125% for high and low N application rates, respectively.

Seasonal Nitrogen Redistribution

Legaz et al. (1982) suggested that at post–blossom, the N concentration in the spring leaves decreased due to this tissue becoming an N source for the developing fruit. Using 4 year-old 'Valencia' orange trees, daily root N uptake was lower during

dormancy, increased during flowering and was highest during fruit set, and later decreased towards the end of the summer and autumn flushes. The greatest accumulation of N absorbed from fertilizer (with respect to the total N absorbed from fertilizer in the whole tree) was found in the young leaves and roots, followed primarily by twigs and stems, then flowers and fruits.

Kato et al (1982) found that total N contents decreased in both bark and wood during the sprouting period of 21 year-old 'Satsuma' mandarins. Greatest decreases in N were found in parts with higher concentrations of N (i.e. leaves, shoots, and fine roots). It was also concluded that the trunk and large roots are main N reservoirs for new shoot development. The N was reserved mainly as protein, free proline, arginine, and asparagines. Protein decreased in all plant parts in proportion to total N in the plant part. Proline decreased mainly in the leaves and bark, arginine in wood of shoots and asparagines in bark of fine roots.

Crop and Environmental Models
Current Citrus Models

Few predictive models have been developed specifically for use in citrus production. Most models have been designed for specific applications, with a general user in mind. These models predict population and/or crop damage caused by citrus pathogens (Timmer and Zitko, 1996), and scale insects (Aris and Browning, 1995). Other citrus models are used for irrigation scheduling (Xin et al., 1997), and crop flowering (Bellows and Morse, 1986; Valiente and Albrigo, 2000).

Environmental Models

Nitrogen leaching from agricultural soils represents both an economic loss to the farmer and potential groundwater pollution. Mathematical models can be used to assess

crop N-fertilizer requirements and to predict effects of N fertilizer management practices on potential nitrate leaching and how it affects groundwater quality. The understanding of solute movement and transport has increased in the last 30 years. Increased environmental concerns pertaining to the runoff and leaching of agricultural chemicals and fertilizer elements in the surface and groundwater has resulted in development and use of computer simulation models to predict transport of potential pollutants in agricultural systems. These models include Nitrate Leaching and Economic Analysis Package (N-LEAP) (Follett et al., 1994), Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) (Reck, 1994; Reyes et al., 1994), Drainage-Modified (DRAINMOD) (Saleh et al, 1994; Verma et al., 1995), Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) (Minkara et al., 1995; Saleh et al., 1994), Leaching Estimation and Chemical Model (LEACHM) (Jemison et al., 1994), and Nitrogen, Carbon, Soil, Water And Plant (NCSWAP) (Jabro et al., 1993).

These models could be applied to citrus production to predict or estimate the depth of N leaching below the crop root zone. Most of these models are deterministic, non-steady state, and comprehensive. They typically require a large number of soil physical, hydraulic, and chemical characteristics for each soil layer, soil N transformation components, weather data, and environmental information to determine N fate and leaching depths. Use of these models for the prediction of N fate under agricultural production conditions has met with mixed results (Kiniry et al., 1997). Jabro et al. (1993) found that neither LEACHM nor NCSWAP successfully predicted nitrate leaching below 1.2 m in a silt loam soil. Jemison et al. (1994) reported accurate predictions using LEACHM in manure fertilized corn crops.

Crop Models

Crop-Environment Resource Synthesis (CERES) was developed to model growth and yield of grain crops (Jones and Kirniry, 1987; Kiniry and Bockhot, 1998; Kiniry et al., 1997; Lizaso et al., 2001; Saseendran et al., 1998). CROPGRO was initially developed as a family of crop-specific models for the prediction of legume and vegetable crops (Hoogenboom et al., 1994; Jones et al., 1991; Wagner-Riddle et al., 1997). These are process-oriented models for the simulation of vegetative growth and reproductive development. They predict dry matter growth (Shen et al., 1998), crop development (Batchelor et al., 1994; Batchelor et al., 1997; Piper et al., 1996) and final yield (Batchelor et al., 1996; Heinemann et al., 2000) for a range of agronomic crops. Inputs are daily weather data, soil profile characteristics, and crop management conditions (Gijsman et al., 2002). Crop and soil water (Hoogenboom et al., 1994; Gabrielle et al., 1995; and Xie et al., 2001), N (Gabrielle and Kengni, 1996; Quemada and Cabrera, 1995; and Sexton et al., 1998), and C balances are modeled. These models have been combined into the DSSAT (Decision Support System for Agrotechnology Transfer) software (Hoogenboom et al., 1994; Jones and Luyten, 1998).

Conclusions

Considerable research and resources have been devoted to improving our understanding of how cultural, soil, and environmental factors influence biomass and N accumulation during citrus tree development. However, these studies compared tree component dry weights and N accumulations with tree age and not a measure of tree size. Tree size is not only a function of tree age, but soil, environmental, and horticultural factors as well. Therefore, correlation of dry weights and N accumulations with tree size

would provide a better relationship for modeling purposes. Factors affecting citrus root distribution have been studied under Florida soil and environmental conditions. Many of these studies were performed in groves with lower tree densities and different irrigation methods than those currently used in Florida citriculture, and on trees grafted on rootstocks that are no longer in use. Thus, information on the effect of tree size on root length density distribution changes for current production systems are lacking. Likewise, root length density distributions for mature trees on currently used rootstocks grown on Florida sandy soils have not been determined.

Seasonal maximum daily water uptake rates under Florida environmental conditions have been determined for trees grown on flatwood soils with fluctuating water tables. However, maximum daily water uptake rates for mature citrus trees have not been measured for trees grown on excessively drained "Ridge soils". Likewise, reduction in daily citrus water uptake with decreased soil water potential has not been determined for sandy soils. Citrus N uptake rates have been determined for seedlings and relatively small trees grown in lysimeters. These rates may not reflect uptake rates of mature citrus trees at the field-scale.

Much data on citrus growth, root distribution, water requirements, and N uptake rates are needed to attain the level of crop modeling currently available for agronomic crops. Obtaining these data are difficult due to the size of mature citrus trees compared with agronomic crops, and the inability to follow a cohort of trees from planting to maturity. Biomass, N accumulation, and spatial root length density changes as affected by tree size, and water and N uptake dynamics of mature trees under Florida "Ridge" conditions will be presented in the following chapters.

CHAPTER 3
CITRUS BIOMASS AND NITROGEN ACCUMULATION

Introduction

Citrus is native to the subtropical and tropical regions of Asia and the Malay Archipelago (Webber and Batchelor, 1943). Citrons were introduced into Europe via the Middle East as early as 300 BC, with lemons and sweet oranges following some 15 and 17 centuries later, respectively. Citrus is well adapted to Florida soil and environmental conditions and proliferated in the costal settlements of Florida by the mid 16th century and was in commercial production by the mid 1800s.

Nitrogen application rate studies in citrus have emphasized the effects of timing and amount on increased canopy volume and yield (Sites et al., 1953; Reitz, 1956; Reuther et al., 1957; and Koo, 1979). However, optimum plant growth depends upon maintenance of an efficient balance between roots and shoots (Kramer and Boyer, 1995). Roots are dependent on shoots for carbohydrates, growth regulators, and some organic compounds, while the shoots of a plant are dependent on the roots for water and nutrients. The root to shoot ratio varies widely among species, with age, and with environmental conditions. Understanding the dynamics of root and shoot development with time is essential when determining biomass and N accumulation, and soil water and nutrient uptake dynamics.

Caruso et al. (1999) found that the relative proportion of leaves and twigs to total tree dry weight decreased with tree age. Therefore, relative proportions of total dry matter

and N accumulation in different tree components change with age of perennial crops due to the increase in weight of larger branches and trunks of older trees to support the increased tree biomass. Similar changes occur in annual crops with increase in biomass between emergence and harvest. However, as with annual crops, tree size is not dependent on age alone; rootstock (Castle, 1978, 1980), crop nutrition (Feigenbaum et al. 1987), irrigation (Parsons et al., 2001), and restriction of the root system (Mataa and Tomingag, 1998) can limit growth of a citrus tree. Thus, these factors can result in trees of equal age being very different in size, biomass, and N content.

Many crop models such as CERES, CROPGRO, and DSSAT determine the effect of assimilate costs for vegetative and reproductive growth and N budget through C and N balances with increase in crop biomass on water and N uptake, growth, and yield of agronomic crops (Gabrielle and Kengni, 1996; Quemada and Cabrera, 1995; and Sexton et al., 1998). Likewise, optimal irrigation and nutrient management is dependent upon the estimation of biomass and N content in citrus trees. Therefore, the relationship of tree size to biomass and N accumulation is needed.

Previous studies have correlated long-term citrus tree biomass and N accumulation with tree age (Cameron and Appleman, 1935; Cameron and Compton, 1945; Feigenbaum et al., 1987; Kato et al., 1984; Mattos, 2000). Leaves of 3.5, 7, and 15 year-old 'Valencia' trees in California contained from 40 to 50% of total tree N, while twigs and shoots contained approximately 10% of total N (Cameron and Appleman 1935; Cameron and Compton, 1945). Trunk and branches contained from 20 to 30% of total tree N, approximately half of which was in the bark, a tree component that represents only 5% of the total dry mass. The roots contained from 15 to 20% of tree N, half or

more of which was in the bark (5% of the dry mass of the tree). The biomass proportions for 7 year-old 'Hamlin' orange trees grown under Florida conditions reported by Mattos (2000) were more similar to the 10 year-old trees cited above than the 3.5 year-old trees (Table 1). Nitrogen concentration was lowest in the trunk and taproot of these trees. The N concentration of leaves (2.1 to 2.6 %), twigs (0.4 to 0.8 %), and roots (0.6 to 1.7 %) varied with tissue age. Younger tissue tended to have greater N concentration compared with older tissues. Kato et al. (1984) and Feigenbaum et al. (1987) harvested older citrus trees (21 and 22 years old, respectively). Leaves comprised a smaller fraction of total biomass in both studies compared with branches and total roots. The leaves of these older trees contained a lower proportion of total tree N than the branches, equal to the proportion of N in the roots (Table 3-1). None of the above studies related biomass or N measurements to tree size parameters such as canopy volume or trunk cross-section area.

Biomass and N distribution relationships based on tree size measurements as opposed to tree age could provide more generic information needed for modeling tree growth and N cycling in citrus production systems. Therefore, the hypotheses to be tested in the following studies were: 1) functional relationships can be defined that correlate biomass and N partitioning of specific tissue categories with tree size using generic growth indicators such as canopy volume or trunk area, and 2) rootstock has a significant effect on citrus biomass and N partitioning. Such relationships can be used to determine citrus N budgets and develop specific fertilizer recommendations that will provide adequate N for growth and production while protecting groundwater from nitrate contamination. Thus, a non-destructive method of estimating an N budget is needed for trees of unknown or mixed ages. Therefore, the objectives of the following studies were

Table 3-1. Citrus biomass and nitrogen distribution by tree age as reported by different studies.

Authors	Trees (n)	Location	Cultivar	Age (Yrs)	Plant Tissue	Biomass (% Total)	N (% Total)
Cameron and Appleman (1935)	15	California	Val.	3.5	Leaves	30.5	61.9
					Branches	38.4	21.0
					Roots	31.1	17.1
Legaz and Primo-Millo (1988)	8	Spain	Val.	4	Leaves	22.5	30.0
					Branches	28.7	18.5
					Lateral roots	45.8	41.2
					Fibrous roots	2.9	10.3
Mattos (2000)	6	Florida	Ham.	6	Leaves	13.9	35.0
					Branches	46.5	28.2
					Lateral roots	25.7	13.4
					Fibrous roots	14.1	23.2
Cameron and Appleman (1935)	4	California	Val.	10	Leaves	18.5	46.7
					Branches	60.7	39.0
					Roots	20.7	14.2
Cameron and Compton (1945)	36	California	Val.	15	Leaves	16.8	45.3
					Branches	61.4	34.8
					Lateral roots	20.4	17.0
					Fibrous roots	1.7	2.9
Kato et al. (1984)	1	Japan	Sat.	21	Leaves	8.6	27.2
					Branches	65.1	44.6
					Lateral roots	19.5	14.3
					Fibrous roots	6.8	14.0
Feigenbaum et al. (1987)	2	Israel	Sham	22	Leaves	7.3	24.6
					Branches	61.0	49.8
					Lateral roots	26.5	19.2
					Fibrous roots	4.3	3.8

to determine: 1) changes in biomass and N distribution with change in tree size, 2) yearly changes in biomass and N content of mature citrus trees, and 3) rootstock effect on mature citrus tree biomass and N distribution. The relationships of canopy volume and mean trunk diameter to biomass and N content for citrus will form the basis of a predictive model to estimate the biomass and N distribution based on size measurements.

Materials and Methods

Citrus trees of various sizes were measured and dissected into constituent parts during a period of 1 year. Representative tissue samples of constituent parts for each tree were weighed and analyzed to estimate total dry mass, relative percentage dry mass, and N content of the various tree components. These data were used to determine N allocation between different tree constituents.

Experiment 1 – Mature Citrus Biomass and N Distribution

Two sets of six trees each were dissected in February 2001 and January 2002 at the Water Conserv II site near Winter Garden in western Orange county, Florida. Both sets of trees were 14 year-old 'Hamlin' orange trees planted in 1987 at a spacing of 3 m between trees in the row and 6 m between rows resulting in a tree density of 556 trees ha^{-1}. Three trees of each set were budded on Swingle citrumelo (*Citrus paradisi* Macf. x *Poncirus. trifoliata* (L.) Raf) rootstock, and the remaining three trees of each set on Carrizo citrange (*C. sinensis* L. Osbeck X *P. trifoliata* L. Raf.) rootstock. All trees had been fertigated at an annual rate of 240 kg N ha^{-1}. The trees were irrigated (and fertigated) with reclaimed water containing approximately 7 mg NO_3-N L^{-1}.

Experiment 2 – Biomass and N Accumulation with Increase Tree Size

A third set of seven 'Valencia' trees on Swingle citrumelo rootstock were dissected at the K.D. Revell grove owned by Cargill, Inc. near Fort Meade in southern Polk county, Florida. Fresh, dry, and N weights were determined for the same constituent parts as in experiment 1. These trees had been fertilized using dry chemical fertilizer three or more times per year and irrigated with well water.

Site Descriptions

The soil series at the Orange county site was Candler fine sand (hyperthermic, uncoated, Typic Quartzipsamment), and at the Polk county site was Zolfo fine sand (sandy siliceous, hyperthermic Grossarenic Entic Haplohumod). These two soils are typical of the central Florida ridge and have a field capacity water content of 0.06 to 0.08 cm cm^{-3} in the upper 1 m. The Candler series consists of excessively drained, very rapidly permeable soils formed from marine deposits. These soils are located in upland areas and typically have slopes of 0-12%. The A and E horizons consist of single-grained fine sand, have a loose texture, and are strongly acidic. A Bt horizon is located at a soil depth of 2 m and includes loamy lamellae of 0.1 to 3.5 cm thick and 5 to 15 cm long. Zolfo series soils are sandy and slightly less well drained than those of Candler. The A horizon consists of fine sand with single-grained, loose texture. The Bh horizon between 4.0 and 5.0 cm consists of fine sand coated with organic matter possessing weak granular to weak fine subangular blocky structure.

Tree Canopy Volume and Trunk Cross-Section Area

Changes in canopy volume have been used in fertilizer rate experiments as measures of tree growth (Whitney et al., 1991). Therefore, tree measurements were determined for the purpose of correlating biomass and N concentration of various tree components to tree size. Canopy diameter of each tree was measured in the row (in-row) and across the row (cross-row) at a height of 1.5 m above ground level. Tree height and hedgerow intercept measurements were made using a 5 m graduated pole. Hedgerow intercept is the height from the ground to the point at which the canopies of two trees meet in the row. These measurements have been used by Whitney et al. (1991) to determine canopy volume based on a spheroid model (Equation 3-1). Trunk diameters 5

cm above the ground were determined for each tree by measuring in-row and cross-row dimensions. Trunk cross-sectional areas (TCSA) were determined for each tree assuming an oval shape.

$$TCV = \frac{\pi}{4} * Ir * Cr * Ht * \frac{(1-(1-(\frac{Int}{Ht})^2))}{3}$$

Equation 3-1

Where:

TCV = Tree canopy volume (m^3)

Ir = In-row spacing (m)

Cr = Cross-row spacing (m)

Ht = Canopy height (m)

Int = Canopy intercept height (m)

Tree Biomass Fresh Weight

Fresh weight of the leaves, twigs <7 mm, small branches 7 to 15 mm, medium branches 15 to 30 mm, large branches >30 mm, trunk, tap root, small roots <4 mm, medium roots 4 to 20 mm, and large roots >20 mm were measured in the field. Field weights and three samples of each plant part category were collected for each tree using the following protocol: Twigs less than 7 mm in diameter and attached leaves were cut from the tree with leaves intact. These twigs were placed into a plastic container and weighed on a battery powered field-portable balance. During cutting, one twig out of 20 was placed into a separate container as they were cut and were weighed separately. Leaves were removed from the twigs in this container while still in the field. Fresh weights of these subsamples were measured. Branches 7 mm in diameter and greater were cut into 15 to 30 cm segments, separated into the three size ranges noted above, and

weighed separately. Two to three samples equal to 5% of the fresh weight of each size category were removed from each container and placed into labeled plastic bags. Any leaves attached to these branches were removed and weighed prior to weighing the branch segments. The trunk and taproot were cut into pieces and weighed, and three longitudinal slices of each were retained as separate samples.

The trees were planted 3.1 m in row and 6.2 m between rows. Therefore, the roots were cut to a depth of approximately 0.3 m using a shovel in a rectangle 3.1 m in-row x 6.2 m across-row with the tree stump at its center. The bulk of the root system was extracted using a front-end loader equipped with a root rake. All roots were removed from the excavation to a depth of 1 m, washed, blotted dry, separated into size categories, and weighed in the field.

Sample Processing and Nitrogen Analysis

The leaf area of 50 random leaves from each sample was measured. Each branch segment of each sample was cut into at least five disks of approximately 0.5 to 1 cm thick that facilitated the removal of bark from the wood. Likewise, the bark was removed from each horizontal trunk slice. The bark and wood from the branch and trunk disks were weighed separately to determine the fresh mass proportion of bark to wood for each size category.

Samples were dried at 70 C to a constant weight before recording dry weight. Total tissue dry weight for each tree was determined by multiplying fresh weights by the respective tissue dry matter content. All tissues were ground using a Cyclotec mill (1093 Sample Mill, Tecator manufacturing, Sweden) for the leaf tissue and Wiley mill model 1 (Arthur Thomas Manufacturing Co., Philadelphia, Pa) for woody tissue. The ground tissues were digested using a Buchi Model K435 12-vessel digestion unit (Buchi

Analytical, Inc., New Castle, DE). The digest was analyzed for total Kjeldahl nitrogen using USEPA method 351.2 using a Buchi model B339 steam distillation instrument (Buchi Analytical, Inc., New Castle, DE.).

Leaf Area, Biomass and N Weight Estimation

Specific leaf area ($cm^2 g^{-1}$) were determined for a 50-leaf subsample by dividing total leaf area by leaf dry weight. Total leaf area was estimated by multiplying the mean specific leaf area by the estimated total dry leaf weight for the corresponding tree. Leaf area index was determined for each tree by dividing the leaf area by the corresponding cross sectional canopy area using the in-row and cross-row measurements. Leaf area index was also determined on a per acre basis by dividing the total leaf area of each tree by the land area occupied by the tree (in-row spacing x cross-row distance). Dry weights for each tissue type of individual tree were estimated by multiplying the total field fresh mass by the mean percentage dry mass of three sub samples for each tissue category. Likewise, N accumulation within each tissue type of each tree was estimated by multiplying the total dry weight by the mean N concentration of the three sub samples of each tissue. Total tree dry weight and N accumulation were determined by summing across tissues categories. The above ground dry weight and N accumulations were determined by summing the estimated values for leaf, twig, total branch, and trunk components. Likewise, the below ground biomass and N accumulation was the sum of total root and taproot values. Percentages of total biomass and N weight were determined for each tissue.

Prior to dissecting the second set of mature 'Hamlin' trees in 2002, all fruit was removed and weighed. Representative fruit samples were collected and dried to

determine percentage dry weight and analyzed for N concentration to determine total fruit N accumulation. Leaves and twigs collected in 2002 were separated into current year's growth and prior year's growth. Separate samples were collected for dry weight and N concentration determination.

Statistical Analysis

Since the samples were taken during a 14-month period, the samples from the mature (14 year old) 'Hamlin' trees were treated as repeated measures and analyzed accordingly using the SAS general linear models (GLM) procedure (SAS Institute, Cary, NC). Non-linear regression analysis of tissue masses and percentages of all trees were made considering canopy volumes and mean trunk diameters as independent variables.

<div align="center">

Results

</div>

Mature Citrus Tree Biomass Distribution – Experiment 1

Leaf area was significantly different (P=0.05) for TCV and TCSA, but not for rootstocks (Table 3-2). However, neither mean leaf area index on a per tree basis (10.2 and 9.9 for Carrizo and Swingle trees, respectively) nor on a per acre basis (6.4 and 6.2 for Carrizo and Swingle trees, respectively) were significantly different for tree size or rootstock. Total above-ground and below-ground weights increased on both a fresh and dry basis across the range of TCV and TCSA encountered in this study. Maximum total fresh weight was approximately 160 kg tree^{-1} with TCVs ranging from 28 to 38 m^3 and TCSAs of 80 to 160 cm^2. Maximum dry biomass for the same canopy volumes and trunk cross-sectional areas was approximately 100 kg tree^{-1}. Maximum above-ground biomass (leaves, twigs, branches, and trunk) and below-ground (roots and taproot) was approximately 74 and 26 kg tree^{-1}, respectively.

Table 3-2. Mature citrus tree leaf area and leaf area index as a function of TCV and TCSA.

| | Leaf Area | | Leaf Area Index | |
| | ($m2$ tree^{-1}) | | (m^2 leaf m^{-2} canopy) | |
	Carrizo	Swingle	Carrizo	Swingle
Mean	110.0	103.4	10.2	9.9
Standard Deviation	10.3	24.8	1.2	1.8
Statistical Significance[z]				
TCV[y]	*	*	NS	NS
TCSA	*	*	NS	NS
Rootstock	NS	NS	NS	NS

[z]NS = not significant, *= significant P<0.05, and **= significant P<0.01.
[y]TCV = tree canopy volume, TCSA = tree cross-sectional area.

Mature trees on Carrizo rootstocks had significantly greater (P=0.05) mean dry weight (100 kg tree^{-1}) than those on Swingle (83 kg tree^{-1}), whereas, below-ground biomass was not significantly different (Table 3-3). Significantly higher (P=0.01) percentage of large branch biomass was found for trees grown on Carrizo citrange (23.8 kg tree^{-1}) compared with trees grown on Swingle citrange (15.8 kg tree^{-1}). Thus, percentage total branch biomass was significantly greater (P=0.05) for the Carrizo

Table 3-3. Dry matter accumulation and allocation between tree components for mature 'Hamlin' orange trees as affected by year of sampling, rootstock, and interaction of year and rootstock.

	Dry Weight Accumulation			Dry Weight Allocation											
	Total Mass	Above Ground	Below Ground	Total Leaf	Total Twigs	Branches				Total Trunk	Roots			
						Sm.	Med.	Lrg.	Total		Sm.	Med.	Lrg.	Tap
	(kg dw tree^{-1})			(% of total weight)										
Year 1	97.6	69.2	28.3	12.7	5.8	17.0	12.1	19.1	48.2	3.6	5.1	4.9	9.5	10.1
Year 2	87.8	64.9	26.3	12.4	7.3	15.3	9.0	21.1	45.4	3.9	6.1	6.8	6.4	9.2
	NS^z	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	**	NS	NS
Carrizo	100.3	77.0	26.6	12.2	7.1	16.0	10.5	23.8	50.3	3.9	5.5	6.1	6.9	6.7
Swingle	82.6	54.7	27.9	12.9	6.0	16.1	10.4	15.8	42.3	3.7	5.8	5.7	8.8	13.1
	NS	*	NS	NS	NS	NS	NS	**	*	NS	NS	NS	NS	*
Car Yr1	104.2	79.2	25.0	12.9	6.8	15.7	11.2	25.4	52.3	3.9	4.9	5.6	8.5	5.1
Car Yr2	96.3	74.8	28.2	11.6	7.5	16.4	9.7	22.2	48.3	3.9	6.2	6.6	5.4	8.3
Swi Yr1	87.6	54.3	33.3	12.4	4.3	18.9	13.5	9.5	41.9	3.2	5.6	3.8	11.1	17.7
Swi Yr2	79.4	55.0	24.4	13.3	7.1	14.2	8.3	20.0	42.5	3.9	6.0	6.9	7.3	10.1
	NS	NS	NS	NS	NS	NS	NS	**	NS	NS	NS	NS	NS	NS

^{z}NS = not significant, *= significant P<0.05, and **= significant P<0.01.

citrange roostock trees. On a percentage basis, the taproot biomass was significantly greater (P=0.05) for trees on Swingle than those on Carrizo.

Although tree weights appeared to be less in 2002 compared with 2001, total dry weight and dry weights of tree components were not significantly different at the P=0.05 level (Table 3-3). Leaf weights represented 12 to 14% of total tree dry weight, while total branch weights (twigs, total branches, trunk) accounted for 49 to 63% of total tree weight. Dry matter allocation to tree roots was highly variable in all three studies, but averaged in the 19 to 21% range.

Total above-ground N accumulation was significantly affected by TCV and TXA at the P=0.05 level (Table 3-4). Leaf, branch, and root N comprised approximately 45, 35, and 20% of total tree N, respectively. Dry weight allocation to leaves, twigs, small branches, medium branches, and trunk were similar for both rootstocks. However, Carrizo trees had almost 50% more N in large branches compared with Swingle. Mean total N accumulation by large roots and taproot was greater for trees on Swingle compared with those on Carrizo. Nitrogen concentrations were not significantly different (P=0.05) within tissues on each rootstock (data not shown), thus differences in percentage of total N mass of each tissue category were due to differences in biomass.

Biomass Changes with Increase in Tree Size – Experiments 1 and 2

Data from experiments 1 and 2 were combined to determine relationships between dry weight and N accumulation and tree size indices such as TCV or TCSA. TCV increased linearly as TCSA increased (Fig. 3-1). Likewise, total leaf area per tree was linearly proportional to both TCV (Fig. 3-2A) and TCSA (Fig. 3-2B). Leaf area

Table 3-4. Nitrogen accumulation and allocation between tree components for mature 'Hamlin' orange trees as affected by year of sampling, rootstock, and interaction of year and rootstock.

	Nitrogen Accumulation			Nitrogen Allocation												
	Total Mass	Above Ground	Below Ground	Total Leaves	Total Twigs	Branches				Total Trunk	Roots			
						Sm.	Med.	Lrg.	Total		Sm.	Med.	Lrg.	Tap
	(kg N tree⁻¹)			(% of total weight)										
Year 1	0.81	0.60	0.21	38.3	8.2	10.0	6.0	9.0	24.9	2.01	10.1	6.1	5.5	4.8
Year 2	0.77	0.57	0.20	36.5	8.3	8.6	4.8	10.8	24.2	2.3	10.1	7.0	3.6	4.9
	NS^z	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	**	NS
Carrizo	0.87	0.65	0.22	36.4	8.5	9.2	5.4	11.5	26.1	2.3	10.1	7.4	4.2	3.5
Swingle	0.69	0.50	0.19	38.4	8.0	9.2	5.3	8.2	22.6	2.1	10.1	5.6	4.8	6.4
	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	*	NS	NS
Car Yr1	0.87	0.66	0.21	38.1	8.8	9.4	5.6	11.6	26.6	2.2	9.4	7.3	4.9	2.7
Car Yr2	0.86	0.64	0.22	34.7	8.1	9.1	5.1	11.4	25.6	2.5	10.7	7.6	3.4	4.4
Swi Yr1	0.71	0.50	0.21	38.6	7.4	10.9	6.5	5.0	22.3	2.0	11.1	4.4	6.4	7.9
Swi Yr2	0.68	0.51	0.17	38.2	8.4	8.0	4.4	10.3	22.7	2.2	9.5	6.4	3.7	5.5
	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS

^{z}NS = not significant, * = significant P<0.05, and ** = significant P<0.0
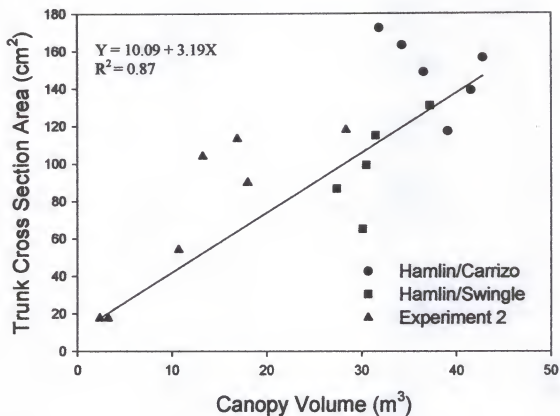
Fig. 3-1. Tree canopy volume as a function of trunk cross sectional area for trees from experiments 1 and 2.
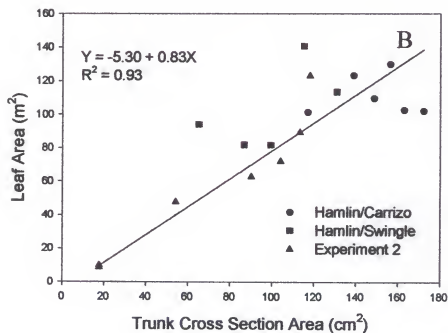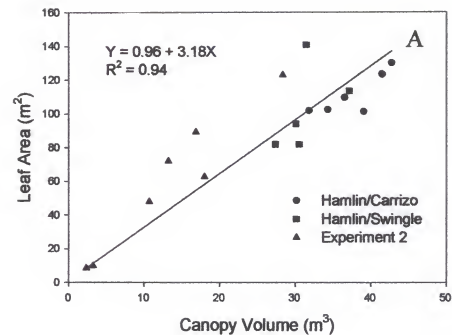
Fig. 3-2. Leaf area expressed as a function of tree canopy volume (A) and trunk cross section area (B).

index on a tree basis (LAI_t) increased rapidly from 4 to 10 as TCV increased from 2 to 10 m^3 (Fig. 3-3A) and TCSA increased from 20 to 80 cm^2 (Fig. 3-3B). Little increase in LAI_t was observed with increasing TCV and TCSA beyond 10 m^3 and 80 cm^2, respectively. Likewise, leaf area index on an acre basis (LAI_a) increased from 1 to 6.3 for the same ranges of TCV and TCSA.

Citrus dry weight accumulation for all tree components increased linearly with increased TCV and TCSA (Fig. 3-4 and Fig. 3-5). Regression coefficients, r^2, and root mean square error (RMSE) values for dry weights of all tissues vs. TCV and TCSA are provided in Tables 3-5 and 3-6, respectively. Coefficients of determination (r^2) were generally higher for each tissue category when compared with TCV than with TCSA. Biomass weights for twig, trunk and root categories varied greatly, resulting in lower r^2 and higher RSME values. The medium branch masses varied more than the small or large branch categories, possibly indicating inconsistent and/or incomplete separation of tree components into appropriate diameter ranges. Correlations of trunk and taproot weights with TCV and TCSA were poor compared with those for other tree components. Variation in dry matter allocation to root and tap root were apparently due to differences in root density distribution of the two rootstocks used in this study.

Dry matter accumulation in above-ground biomass increased from 60 to 75% across a range of 5 to 40 m^3 and 10 to 160 cm^2 for TCV (Fig. 3-6A) and TCSA (Fig. 3-7A), respectively. Leaf biomass declined from approximately 20% of total biomass for trees with TCV of less than 5 m^3 and for TCSA values below 20 cm^2, to approximately 12% of total biomass for trees with TCV and TCSA values greater than 30 m^3 and 160
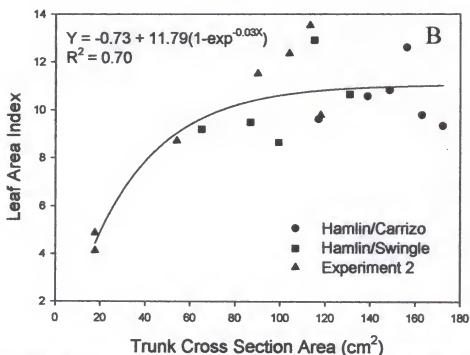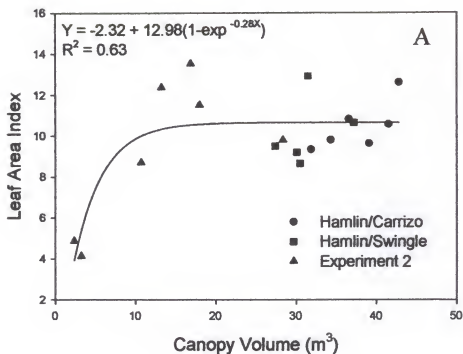
Fig. 3-3. Leaf area index on a tree basis expressed as a function of tree canopy volume (A) and trunk cross-section area (B).

Fig. 3-4. Total (closed), above-ground (open), and below-ground (gray) biomass (A); leaf (closed) and twig (open) biomass (B); total branch (closed) and trunk (open) biomass (C); and total root (closed) and taproot (open) biomass (D) accumulation as a function of tree canopy volume for 'Hamlin'/Carrizo- experiment 1 (O),'Hamlin'/Swingle(□),and experiment 2 (Δ) trees.

Fig. 3-5. Total (closed), above-ground (open), and below-ground (gray) biomass (A); leaf (closed) and twig (open) biomass (B); total branch (closed) and trunk (open) biomass (C); and total root (closed) and taproot (open) biomass (D) accumulation as a function of trunk cross section area for 'Hamlin'/Carrizo - Experiment 1 (O), 'Hamlin'/Swingle – Experiment 1 (□), and Experiment 2 (Δ) trees.

Table 3-5. Linear regression analysis of dry weight and N accumulation in different tree components as related to tree canopy volume (TCV)[z].

	Y_0	a	R^2	RMSE[y]	P
	Dry Weight (kg tree^{-1})				
Total Mass	-2.21	2.79	0.97	0.15	<0.0001
Above Ground	-2.09	1.95	0.96	0.17	<0.0001
Below Ground	0.21	0.72	0.91	0.27	<0.0001
Leaves	0.09	0.36	0.95	0.20	<0.0001
Twigs	0.26	0.13	0.76	0.49	<0.0001
Sm. Branches	-0.57	0.37	0.90	0.29	<0.0001
Med. Branches	-0.31	0.23	0.80	0.43	<0.0001
Lg. Branches	-.24	0.36	0.82	0.53	<0.0001
Total Branches	-2.47	1.25	0.92	0.27	<0.0001
Trunk	0.54	0.07	0.72	0.36	<0.0001
Sm. Roots	0.41	0.13	0.87	0.27	<0.0001
Med. Roots	0.32	0.14	0.83	0.33	<0.0001
Lg. Roots	-0.24	0.18	0.85	0.37	<0.0001
Tap Root	0.06	0.12	0.60	0.57	<0.0001
	Nitrogen Weight (g tree^{-1})				
Total Mass	-3.24	23.41	0.97	0.16	<0.0001
Above Ground	-7.28	17.52	0.96	0.17	<0.0001
Below round	5.51	5.36	0.92	0.23	<0.0001
Leaves	3.50	8.70	0.92	0.24	<0.0001
Twigs	0.09	1.83	0.85	0.34	<0.0001
Sm. Branches	-3.32	2.04	0.96	0.20	<0.0001
Med. Branches	-1.28	1.00	0.78	0.45	<0.0001
Lg. Branches	-3.46	2.44	0.88	0.32	<0.0001
Total Branches	-11.31	5.71	0.94	0.23	<0.0001
Trunk	2.80	0.35	0.65	0.40	<0.0001
Sm. Roots	5.38	1.85	0.86	0.28	<0.0001
Med. Roots	1.82	1.34	0.88	0.29	<0.0001
Lg. Roots	-1.10	0.88	0.89	0.32	<0.0001
Tap Root	0.68	0.55	0.63	0.53	<0.0001

[z] $Y = Y_0 + aX$ where $X = TCSA$, and Y_0 and a are regression coefficients

[y] RMSE dry weight kg dw tree^{-1}, and N accumulation = g N tree^{-1}

Table 3-6. Linear regression analysis of dry weight and N accumulation in different tree components as related to trunk cross-sectional area (TCSA)[z].

	Y_0	a	R^2	RMSE[y]	P
Dry Weight (kg tree[-1])					
Total Mass	-7.23	0.70	0.93	0.23	<0.0001
Above Ground	-5.67	0.50	0.93	0.24	<0.0001
Below Ground	-1.20	0.19	0.89	0.29	<0.0001
Leaves	-0.65	0.09	0.94	0.22	<0.0001
Twigs	-0.04	0.04	0.68	0.47	<0.0001
Sm. Branches	-1.13	0.09	0.82	0.40	<0.0001
Med. Branches	-0.84	0.06	0.80	0.43	<0.0001
Lg. Branches	-.94	0.05	0.78	0.42	<0.0001
Total Branches	-5.17	0.33	0.91	0.30	<0.0001
Trunk	0.38	0.02	0.70	0.36	<0.0001
Sm. Roots	0.10	0.04	0.90	0.24	<0.0001
Med. Roots	-0.08	0.04	0.91	0.25	<0.0001
Lg. Roots	-0.53	0.04	0.78	0.45	<0.0001
Tap Root	-0.19	0.03	0.61	0.57	<0.0001
Nitrogen Weight (g tree[-1])					
Total Mass	-47.83	6.00	0.94	0.22	<0.0001
Above Ground	-41.41	4.51	0.94	0.23	<0.0001
Below round	-5.36	1.41	0.92	0.24	<0.0001
Leaves	-15.39	2.32	0.93	0.23	<0.0001
Twigs	-3.29	0.46	0.82	0.37	<0.0001
Sm. Branches	-6.75	0.49	0.89	0.31	<0.0001
Med. Branches	-3.52	0.27	0.77	0.47	<0.0001
Lg. Branches	-5.69	0.47	0.85	0.38	<0.0001
Total Branches	-23.36	1.50	0.92	0.27	<0.0001
Trunk	1.97	0.10	0.82	0.39	<0.0001
Sm. Roots	0.92	0.51	0.89	0.25	<0.0001
Med. Roots	-1.48	0.38	0.91	0.25	<0.0001
Lg. Roots	-2.65	0.21	0.82	0.40	<0.0001
Tap Root	-0.23	0.13	0.58	0.56	0.0002

[z] $y = y_0 + ax$ where x = TXA, and y_0 and a are regression coefficients
[y] RMSE dry weight kg dw tree[-1], and N weight = g N tree[-1]

cm^2, respectively (Figs. 3-6B and 3-7B). Likewise, twig biomass decreased from 11 to 6% of total biomass for trees of the corresponding size categories. Total branch dry weight increased from 15 to 45% as trees matured, while trunk biomass decreased from 12% for young trees to 3% for mature trees (Figs. 3-6C and 3-7C). Few consistent trends were found when comparing root biomass with tree size (Figs. 3-6D and 3-7D), which may be due to problems in recovering all root tissue or differences in root biomass distribution between the two rootstocks used in this study.

Nitrogen Distribution

Mature Citrus Tree Nitrogen Distribution – Experiment 1

As was the case with dry biomass, total N accumulation was greater for trees on Carrizo rootstock (870 g tree^{-1}) than for trees on Swingle (690 g tree^{-1}). Total and above-ground N accumuluation were significantly (P=0.01) affected by TCV and TCSA, whereas below-ground N accumulation was not (Table 3-4). Rootstock, year, and the interaction of rootstock and year effects were not correlated with TCV or TCSA. Nitrogen concentration was not significantly different compared with TCV, TCSA, rootstock, or year for any of the tissues sampled (Table 3-7). Therefore, N content trends were similar to those for dry weight. Percentage tissue N concentration compared with total tree N weight was not significantly different for tree size, rootstock, or year with the exception of branches greater than 30 mm in diameter. Trees grown on Carrizo citrange had significantly greater (P=0.05) N in larger branches and total branches compared with TCV (Table 3-4).
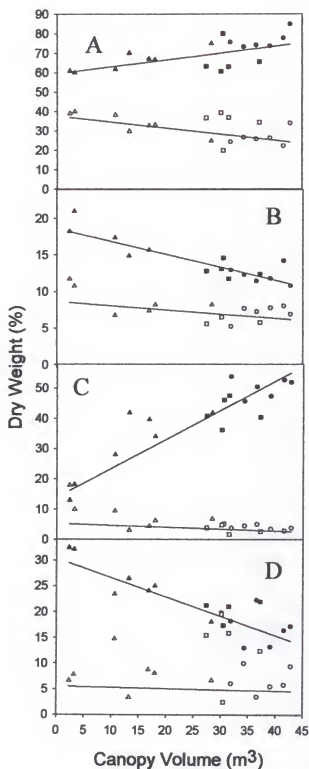
Fig. 3-6. Dry weight allocation to above-ground (closed), and below-ground (open) biomass (A); leaf(closed) and twig (open) biomass (B); total branch (closed) and trunk (open) biomass (C); and total root (closed) and taproot (open) biomass (D) as a function of canopy volume for 'Hamlin'/Carrizo - experiment 1 (O), 'Hamlin'/Swingle – experiment 1 (□), and experiment 2 (Δ) trees.
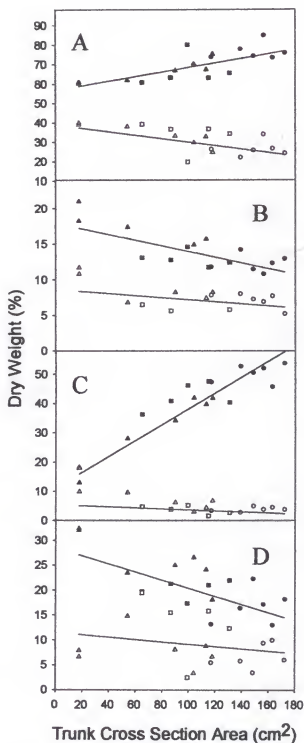
Fig. 3-7. Dry weight accumulation to above-ground (closed), and below-ground (open) biomass (A); leaf (closed) and twig (open) biomass (B); total branch (closed) and trunk (open) biomass (C); and total root (closed) and taproot (open) biomass (D) as a function of trunk cross section area for 'Hamlin'/Carrizo - experiment 1 (O), 'Hamlin'/Swingle – experiment 1 (□), and experiment 2 (Δ) trees.

Table 3-7. Mature citrus tree tissue N concentration as a function of year sampled and rootstock.

Plant Tissue	Year Sampled		Rootstock	
	2001	2002	Carrizo	Swingle
			(%)	
Leaves	2.47	2.32	2.47	2.46
Twigs	1.28	1.00	1.09	1.14
Small Branches - Bark	1.16	1.24	1.22	1.11
Small Branches - Wood	0.30	0.31	0.33	0.28
Med. Branches – Bark	1.11	1.28	1.13	1.08
Med. Branches – Wood	0.29	0.32	0.30	0.28
Large Branches – Bark	1.16	1.33	1.06	1.30
Large Branches – Wood	0.38	0.34	0.42	0.33
Trunk – Bark	1.29	1.36	1.33	1.14
Trunk – Wood	0.42	0.44	0.43	0.42
Fibrous Roots	1.55	1.38	1.61	1.51
Medium Roots	1.04	0.85	1.10	0.97
Large Roots	0.48	0.47	0.50	0.47
Tap Root	0.45	0.45	0.47	0.39

Statistical Significance[z]	
Year	NS
Rootstock	NS
Year X Rootstock	NS

[z] NA = No significant difference at the P=0.1 level.

Nitrogen Balance

Leaf and twig dry weight accumulation during the previous 12 months was significantly greater (P=0.05) for trees grown on Carrizo (3963 and 5717 g tree[-1], respectively) compared with trees grown on Swingle (3312 and 4525 g tree[-1], respectively). Total N content for these tissues were 145 and 127 g tree[-1] for Carrizo and Swingle, respectively. Mean fruit N accumulations for the two rootstocks were 302 and 258 g tree[-1] for trees on Carrizo and Swingle, respectively. Assuming a conservative 5% increase in N accumulation in all tissues other than leaves and twigs due to increase in biomass in 2001, the resulting increase in N content was 24 and 18 g tree[-1] for Carrizo and Swingle

trees, respectively. Therefore, the total estimated increases in N content for 2001 were 471 and 403 g tree^{-1} for trees grown on Carrizo and Swingle rootstocks, respectively. The amount of fertilizer N applied in 2001 was approximately 503 g tree^{-1}, resulting in apparent fertilizer N uptake efficiencies (FNUE) of 93.6 and 80.1% for Carrizo and Swingle rootstocks, respectively. However, if the 58 g tree^{-1} of N contained in the 1273 mm ha^{-1} of reclaimed water applied over the 12-month period is considered, NUE decreases to 84.0 and 71.8% for Carrizo and Swingle rootstocks, respectively.

Nitrogen Change with Increase in Tree Size – Experiments 1 and 2

Nitrogen accumulation increased linearly with increasing TCV and TCSA from 5 to 40 m^3 and 20 to 160 cm^2, respectively (Figs. 3-8A and 3-9A). Total leaf N mass increased from less than 30 to more than 250 g N tree^{-1} across the range of TCV and TCSA measured (Fig. 3-8B and 3-9B). These increases were about 45% of total tree N for trees with TCVs less than 5 m^3 to 37% for trees with TCVs greater than 35 m^3 (Figs.3-10B and 3-11B). Twig N ranged from less than 10 to greater than 50 g tree^{-1} across the range of trees measured (Figs. 3-8B and 3-9B), but twigs still contained a consistent 9% of total tree N regardless of tree size (Figs. 3-10B and 3-11B). Total N accumulation by branches increased from less than 10 to greater than 200 g N tree^{-1} for trees with TCV of less than 5 and greater than 40 m^3, respectively (figs. 3-8C and 3-9C), which corresponds to an increase in percentage of total tree N from 6 to 27% for corresponding tree sizes (Fig. 3-10C and 3-11C). The proportion of total tree N in the trunk decreased from 5 to 3% (Figs. 3-10C and 3-11C). Regression coefficients, R^2, RSME, and probability values for dry matter and N accumulation within each tissue type are presented in Tables 3-5 and 3-6.
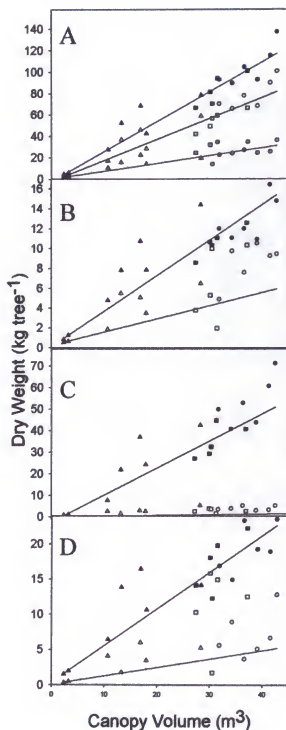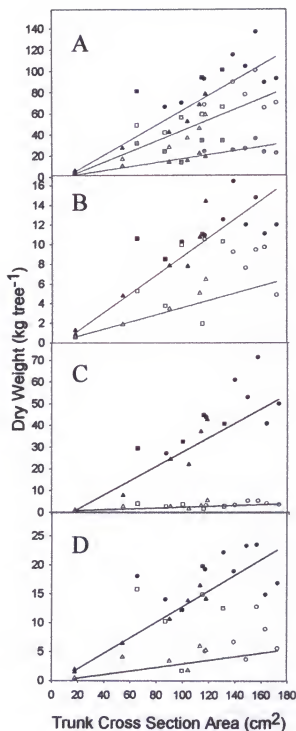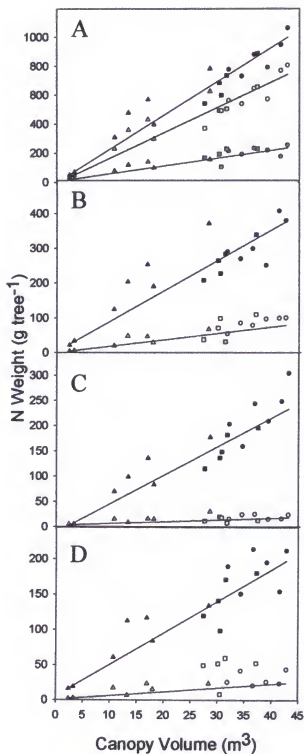
Fig. 3-8. Total (closed), above-ground (open), and below-ground (gray) N weight (A); leaf (closed) and twig (open) N weight (B); total branch (closed) and trunk (open) N weight (C); and total root (closed) and taproot (open) N accumulation (D) as a function of canopy volume for 'Hamlin'/Carrizo - experiment 1 (O), 'Hamlin'/Swingle – experiment 1 (□), and experiment 2 (Δ) trees.
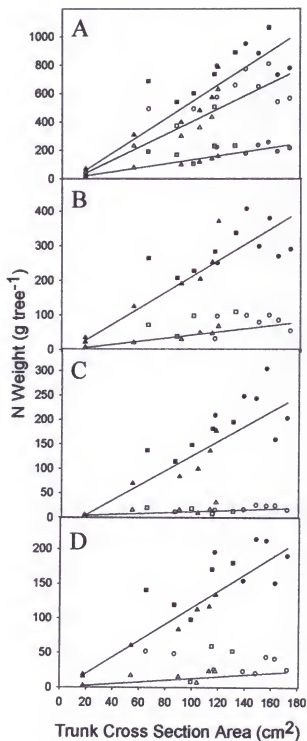
Fig. 3-9. Total (closed), above-ground (open), and below-ground (gray) N weight (A); leaf (closed) and twig (open) N weight (B); total branch (closed) and trunk (open) N weight (C); and total root (closed) and taproot (open) N accumulation (D) as a function of trunk cross section area for 'Hamlin'/Carrizo - experiment 1 (O), 'Hamlin'/Swingle – experiment 1 (□), and experiment 2 (Δ) trees.
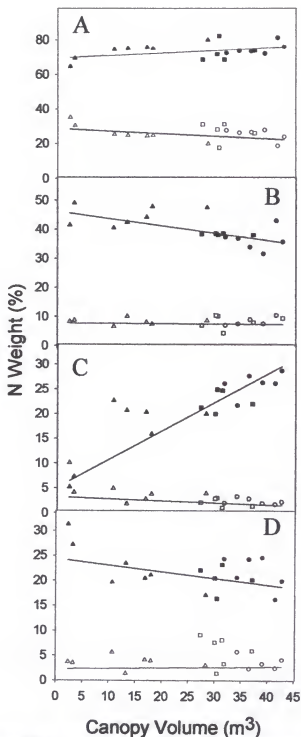
Fig. 3-10. Nitrogen allocation to above-ground (closed), and below-ground (open) N weight (A); leaf (closed) and twig (open) N weight (B); total branch (closed) and trunk (open) N weight (C); and total root (closed) and taproot (open) (D) as a function of canopy volume for 'Hamlin'/Carrizo - experiment 1 (O), 'Hamlin'/Swingle – experiment 1 (□), and experiment 2 (Δ) trees.
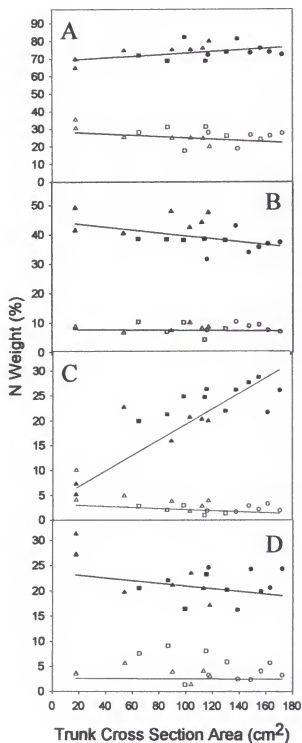
Fig. 3-11. Nitrogen allocation of above-ground (closed), and below-ground (open) N
weight (A); leaf (closed) and twig (open) N weight (B); total branch (closed) and
trunk (open) N weight (C); and total root (closed) and taproot (open) (D) as a
function of trunk cross section area for 'Hamlin'/Carrizo - experiment 1 (O),
'Hamlin'/Swingle – experiment 1 (□), and experiment 2 (Δ) trees.

Discussion

The mature 'Hamlin' trees used in this study were planted at the same time and received the same horticultural inputs (i.e. fertilizer rates, irrigation schedule, and pest control) for the past 14 years. Total leaf area of each tree differed with tree size, but LAI_t and LAI_s appeared to approach maximum values of 10 and 6.5, respectively. The mean LAI_t value of 10 is well within the 9 to 11 range found by Syvertsen and Lloyd (1994) for mature citrus trees. These values are much higher that the 3 or less associated with agronomic row crops (Flenet et al., 1996). Citrus is thought to have developed as an understory plant in subtropical rainforests and so has a high tolerance to shade (Syvertsen and Lloyd, 1994) and therefore developed a dense canopy. A large fraction of citrus leaves found within the inner canopy receive 10% or less of recorded on the outermost leaves (Cohen et al., 1987) The observed LAI would indicate that, on average, 10 layers of leaves exist over each unit area of soil under the tree canopy. This finding has significant implication for light interception and photosynthesis, indicating that citrus is an efficient interceptor of light and allows very little of it to strike the soil surface. Leaves in the interior of a citrus tree are adapted for low light levels and tend to be thinner and flatter than exterior leaves (Mills et al., 1999).

Percentages of total biomass and N in leaf, branch and root tissue compared well with 10 and 15 year old trees harvested by Cameron and Appleman (1935) and Cameron and Compton (1945). However, trees grown on Swingle rootstock were significantly smaller than those grown on Carrizo rootstock. Even though tree size was different, dry weight allocation between tree components remained relatively constant. However, there were significant differences in dry weight accumulation in large branch and total branch

biomass weights for the two rootstocks in this study. Trees grown on Carrizo citrange rootstocks were larger than those of the same age grown on Swingle citrumelo, therefore the difference in large and total branch weights were correlated with tree size as measured by TCV and TCSA. Hence, the percentages of total biomass for specific tree components were similar for both rootstocks, indicating that above ground biomass is partitioned equally based on the relationship of total biomass to tree size. Therefore, if the relationship of total biomass to tree size is known, and the relationship of component partitioning to tree size is also known, then the biomass of each component part can be estimated regardless of rootstock effects on tree size.

The biomass associated with individual tree trunks was related to the height of the crotch formed by the main scaffold limbs of the tree. In citrus nurseries, crotch height is relatively uniform. However, the larger trees used in this study were affected by the freezes of the late 1980s, most notably in 1989. The limb structure of the "Hamlin" trees used in the mature tree portion of this study had to be re-grown, in some cases requiring the entire scaffold limbs and a portion of the upper trunk to be removed. Thus the heights of the trunk to the scaffold limbs were not consistent.

Tree size, biomass, N weight, and apparent FNUE were greater for trees grown on Carrizo citrange rootstock compared with trees grown on Swingle citrumelo, indicating that differences in tree size are directly correlated with FNUE. Differences in FNUE may be due to physiology of the rootstocks themselves or due to the distribution of fibrous roots associated with the various rootstocks. The distribution of root length densities and N uptake rates for the two rootstocks in this study will be the subject of Chapters 4 and 6, respectively.

Assuming that 30% of the N accumulated in new growth tissues came from fertilizer (Dasberg, 1987; Feigenbaum et al., 1987; Legaz et al., 1982), it is concluded that 124 and 108 g of accumulated N originated from the fertilizer inputs. The calculated FNUEs of 84.0 and 71.8% for Carrizo and Swingle rootstocks, respectively, in this study were similar to the 61 to 83% reported by Syvertsen and Smith (1996) for 4-year old grapefruit trees grown in lysimeters. However, mineralized soil N was not included in the estimation. The contribution of soil organic matter and abscised tree parts will be addressed in Chapter 6. Accounting for these sources of N will reduce overall NUE for the citrus trees in this study.

Citrus trees at the Conserv II site were of the same age and similar in size, but the K.D. Revell grove operated by Cargill, Inc. contained trees of various ages due to past replanting of trees. The water and nutrient holding characteristics of the soil at this site were similar to those of the soil at Conserv II. Therefore, it was assumed that trees grown at this site would follow similar biomass and N partitioning characteristics. Total leaf area for trees in both experiments increased linearly with TCV and TCSA. LAI increased rapidly with tree size until the trees were approximately 3-4 years old, after which it stabilized at about 10. This information can be used to parameterize light interception functions for a citrus tree photosynthesis and growth model.

Significant relationships were found between total tree fresh and dry biomass and tree size. The ratio of above-ground to below-ground biomass and N content ranged from a low of 3:2 to a high of 3:1 across the range of tree sizes found in this study. Citrus roots of mature citrus trees extend below 1.8 meters (Castle, 1978 and 1980; Elezaby, 1989; Menocal-Barverena, 2000), but the root system in this study was excavated to a depth of

only 1 m. Therefore, the ratio of above-ground to below-ground biomass may have remained near 3:2 if roots extending below 1 m were included in the total root biomass measurement.

Citrus trees increase in size with time; branches increase in diameter through accumulation of xylem tissue, eventually developing a scaffold branch structure of large-diameter branches. The relationship of total tree biomass and N weight to TCV and TCSA followed a linear function indicating a constant rate of accumulation with increase in tree size as measured by both TCV and TCSA. This result implies that the partitioning of biomass and N accumulation in all plant parts occurs at rates specific to the tree component. Therefore, the total biomass and/or N weight of a citrus tree can be estimated for any tree size.

Percentage biomass and N weight of woody tree parts (large branches and trunk) increased, while those of leaves and twigs decreased with increase in TCV and TCSA. Caruso et al. (1999) found similar results in peaches where the relative proportion of leaf and twig dry weights decreased with tree age. It can be concluded that to support the increase in total tree weight, the biomass and N content of woody branches and trunk increases at a higher rate compared with leaves and twigs. However, it can be concluded that LAI_t is the driving factor in leaf and twig biomass accumulation since the ratio of leaf area to ground area under the canopy remained constant with increase in tree size for medium and large trees. Thus, once the total biomass and N weight of a tree is estimated, the weights of individual tree parts can be estimated based on tree size. Regression equations such as those in Tables 3-5 and 3-6 can be used to simulate biomass and N partitioning in a citrus growth model.

Conclusions

Leaf areas of both young and mature citrus trees were correlated with tree size as measured by TCV and TCSA. Leaf area index increased rapidly for young citrus trees and then equilibrated at approximately 10 by age 3 to 4 years. This information is valuable for the estimation of citrus light interception and total photosynthesis. Change in citrus tree dry weight and N content of the two citrus scions in these studies was shown to be a linear function of TCV and TCSA. Partitioning of biomass and N decreased for leaves and twigs, increased for branches, and remained constant for trunk and taproot tissues with increase in tree size. While mature citrus trees grown on Swingle citrumelo rootstock were consistently smaller than trees of similar age grown on Carrizo citrange, mass partitioning of tree parts were similar for both rootstocks. Thus, with the exception of spatial root length density distribution described in chapter 4, the only effect of the two rootstocks and two scions used in these studies was on tree size relative to TCV and TCSA. Therefore, biomass and N partitioning for specific tissues with tree size can be captured in generic linear relationships. The N balance estimated for mature citrus trees in this study indicated an apparent fertilizer N use efficiency of 60 to 70%.

CHAPTER 4
CITRUS ROOT GROWTH DYNAMICS

Introduction

While the role of roots in anchoring crop plants, particularly tree crops, to the soil should not be taken for granted, the function of roots as absorbing organs for both water and nutrients can not be overemphasized. The structure of a root system is important in determining the pathway and resistance to water and solute uptake, and the volume of soil accessible to crop plants (Kramer and Boyer, 1995). The entrance of water and nutrients into young roots occurs a few cm behind the root tips because of the lack of a functional xylem at the tip and the suberization of root hypodermis and endodermis tissues with age (Tinker and Nye, 2000). Thus, the larger the length of relatively small diameter fibrous roots a crop root system has, the greater the amount of water and nutrients available to it. Likewise, the larger the soil volume a crop root system occupies, the greater the pool of water and nutrients available for uptake.

The goal of fertilizer application should be the placement of nutrients within the crop root zone to insure the most efficient uptake. Maintenance of adequate water and labile nutrient concentrations within soil zones occupied by the crop root system is essential for optimal nutrient uptake. Understanding the spatial distribution of fibrous roots is essential to ensure proper fertilizer placement to improve nutrient uptake and potentially reduce leaching below the root zone.

Several Florida studies have demonstrated that tree size and yield were related to fibrous root density and/or distribution (Castle and Krezdorn, 1975; and Ford 1954a; 1964; 1968; 1969; 1972) in the deep sandy soils of central Florida. Since processes that control non-point source pollution are dynamic and greatly affected by genetic traits and environmental conditions, development of models that can integrate interactive effects of spatial and temporal processes will be critical. However, models providing realistic results will need to include accurate information on root growth dynamics. Modeling of citrus root distribution and the determination of water and nutrient uptake parameters can lead to the development of an expert system for the estimation of water and nutrient depletion and uptake by soil depth. Likewise, nutrient leaching can be estimated due to excessive irrigation or heavy rainfall.

Under Florida growing conditions, the quantity of fibrous roots decreased with depth and lateral distance from the trunk (Elezaby, 1989; Menocal-Barberena, 2000). Eighty percent of citrus fibrous roots were found within a 120 cm radius of the tree trunk and 40% in the upper 30 cm of well-drained sandy soils. Nearly all citrus roots grow within 45 cm of the soil surface where artificial drainage was provided and/or high water tables occured (Calvert et al., 1967; 1977; Ford, 1954a; Ford, 1972; Reitz and Long, 1955).

Fibrous root dry mass densities ranged from 300 to 1200 g m^{-3} (Castle, 1978; 1980). Citrus fibrous root length densities ranged from 0.53 cm cm^{-3} for 'Swingle' citrumelo roots to 2.02 cm cm^{-3} for trifoliate orange (Eissenstat, 1991). Elezaby (1989) reported fibrous root concentration in the 0 to 30 cm soil zone increased from 450 to 1000 g m^{-3} between trees when the in-row distance decreased from 4.5 to 2.5 m due to

overlapping root systems.

Castle and Krezdorn (1975) described two general types of root systems, the first characterized by extensive lateral and vertical development, and the second with intensive higher fibrous root density near the soil surface. Trees on rough lemon, 'Volkamer' lemon and 'Palestine' sweet lime (*C. limettioides* Tan.) typified the extensive type of root system where 50% of the fibrous roots occurred below 70 cm in the soil and produced large, highly-productive trees that dominated the citrus industry in Florida when trees were irrigated less intensively and were set at much lower densities. Unfortunately, rough lemon has been virtually eliminated as a commercial rootstock due to citrus blight disease. Examples of the intensive-type root system were Carrizo citrange and Swingle citrumelo that had few fibrous roots below 70 cm, and the root system was less developed laterally. These rootstocks now dominate the citrus industry in Florida and are well suited for high-density, intensively irrigated plantings.

The following hypotheses were tested: 1) Root distribution is significantly affected by rootstock, and 2) Generic relationships can be developed for well-drained soils that describe citrus root densities at various depths from the soil surface and distances from the tree as a function of tree size. To test these hypotheses, the objectives of this study were to: 1) develop information on spatial root length distribution at different soil positions and depths for two citrus rootstocks, and 2) develop functional relationships that define root length densities at various soil positions and depths as a function of tree size. The relationship of vertical and horizontal root length density distribution to tree size resulting from this study can be used to estimate fibrous root densities in various soil layers for citrus water and nutrient uptake models. This

relationship will provide a scientific basis for the development of water and nutrient components of an expert system for improved citrus irrigation and N management.

Materials and Methods

Sample Collection

The same 19 'Hamlin' and 'Valencia' orange trees used in the previous biomass and N distribution study (Chapter 3) were used to determine the spatial relationship between citrus root length density and tree size. Soil cores were removed once the trees had been cut to the ground but prior to the excavation of the main root system. Cores were taken with a 7.6 cm diameter bucket auger and roots were sampled at 50, 100, and 150 cm from the tree trunk in the row and 50, 100, 150 and 200 cm between tree rows. Samples were collected at 0 to 15, 15 to 30, 30 to 45, 45 to 60, and 60 to 90 cm depths. Each sample was placed into separate plastic bags, sealed, and marked with tree identification, depth and distance from the tree. The samples were placed in a cooler containing ice and were subsequently frozen at −4 C.

Sample Processing and Statistical Analysis

Roots were removed from the soil by washing though an 850 μm sieve. Any debris not passing through the sieve was removed manually, and the roots were separated into size categories by diameter. These categories were <4 mm, 4 to 20 mm and >20 mm. Root lengths for roots 0 to 4 mm in diameter were determined prior to drying using the line intersect method (Newman, 1966). Root length density data from samples collected from the 12 trees at the Water Conserv II site (mature tree study) were analyzed by the general linear model procedure of SAS (SAS Institute, Inc., Cary, NC). Root length density data from the soil samples collected from the trees of various sizes at the Cargill

grove were analyzed using Proc REG in SAS. Regression equations were determined using SigmaPlot (SPSS, Inc., Chicago IL).

<div align="center">**Results**</div>

Mature 'Hamlin' Orange Root Distribution

Soil depth and distance from the tree trunk significantly ($P = 0.01$) affected citrus root length density (Table 4-1). Mean root length density of fine fibrous roots (<4 mm) extracted from soil cores surrounding the 12 mature citrus trees followed a bimodal spatial distribution with depth from the soil surface (Fig. 4-1), and distance from the tree trunk (Fig. 4-2). Mean fine fibrous root density in the upper 15 cm was 1.04 cm cm^{-3}. Densities ranged from 1.9 cm cm^{-3} soil at 50 cm from the tree trunk to 0.7 cm cm^{-3} at 200 cm. Mean densities decreased at the 15 to 30 cm depth to 0.30 cm cm^{-3} and ranged from 0.5 to 0.07 cm cm^{-3} at 50 and 200 cm distances, respectively. Mean densities of fine fibrous roots increased at depths below 40 cm to a maximum at the 60 to 75 cm depth (0.28 cm cm^{-3}) then declined at the 75 to 90 cm depth (0.27 cm cm^{-3}). Densities at the 60 to 75 cm depth were 0.3, 0.3, 0.3, and 0.03 cm cm^{-3} at distances of 50, 100, 150, and 200 cm from the tree trunk, respectively.

Fine fibrous root densities at the 0 to 15 cm depth were generally greater in the in-row orientation than in the cross-row orientation (data not shown). Mean in-row spatial root length densities (0.41 cm cm^{-3}) were greater, but not significantly different from densities for between-row orientation (0.35 cm cm^{-3}) (Table 4-1), because more overlap in root systems from adjacent trees probably occurred in this orientation.

Table 4-1. Mean fibrous (diameter <4 mm) root length density of mature 'Hamlin' orange tree as affected by rootstock, orientation distance, and soil depth.

Mean Root Length Density (cm cm^{-3})

Rootstock		Orientation		Distance from tree (cm)				Soil depth (cm)					
Carrizo	Swingle	In-row	Cross-row	50	100	150	200	0-15	15-30	30-45	45-60	60-75	75-90
0.36	0.41	0.41	0.35	0.49	0.40	0.33	0.17	1.04	0.30	0.16	0.24	0.28	0.27

	P	Significance^z
Rootstock	0.290	NS
Orientation	0.253	NS
Distance	0.002	***
Depth	<0.0001	***
Distance*Depth	0.820	NS
Rootstock* Distance	0.052	*
Rootstock*Depth	0.002	***

^{z}Significance: NS = not significant, * = significant at P=0.1 level, ** = significant at P=0.05 level, and *** = significant at P=0.01level.
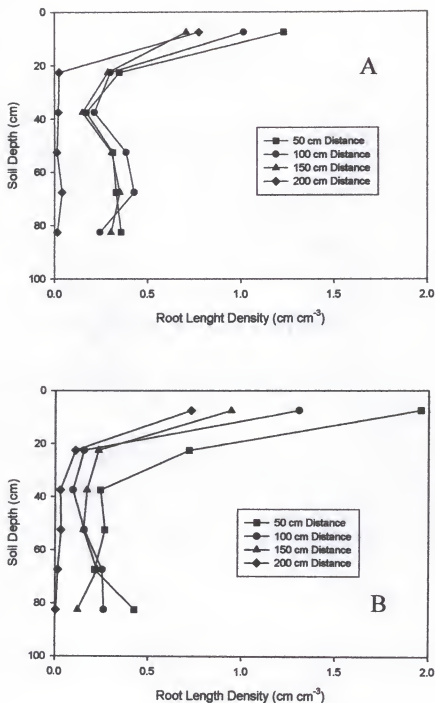
Fig. 4-1. Root length density distribution by depth at 50, 100, 150 and 200 cm distances from the tree trunk between rows of 'Hamlin' orange trees on Carrizo citrange (A) or Swingle citrumelo (B) rootstocks.
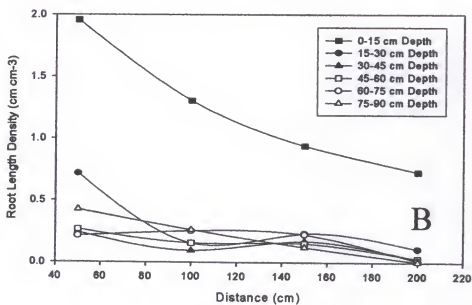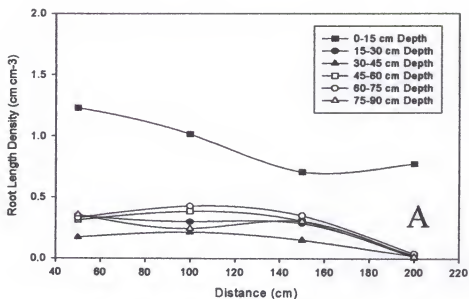
Fig. 4-2. Root length density distribution at 0-15, 15-30, 30-45, 45-60, 60-75, and 75-90 cm depth increments by distance from the tree trunk as affected by distance from the tree trunk for 'Hamlin' orange trees on Carrizo citrange (A) and Swingle citrumelo (B) rootstocks.

Root densities at the 50 cm distance in the cross-row orientation decreased more gradually than did densities at 100, 150, and 200 cm distances. Minimum densities occurred at the 45 to 60 cm depth for the 50 cm distance as opposed to the 30 to 45 cm depth for the 100, 150, and 200 cm distances. Similarly, root densities increased at the 60 to 75 cm depth for the 100 and 150 cm distances, and 75 to 90 cm depth for the 50 cm distance. Spatial root distribution differences between rootstocks were not statistically significant (Table 4-1). Mean root length densities at all depths and distances were 0.36 cm cm^{-3} for trees grown on Carrizo citrange and 0.41 cm cm^{-3} for trees grown on Swingle citrumelo. However, the interaction of rootstock and depth was significant at the P=0.01 level. Trees on Swingle had higher root length densities near the soil surface than did trees on Carrizo (Figs.4-1 and 4-2). Conversely, root length densities were greater for trees on Carrizo between 15 and 75 cm below the soil surface.

Root length densities for the 0 to 15 cm depth ranged from 2.0 to 0.9 cm cm^{-3} soil at distances of 150 cm or less for trees on Swingle rootstock. Densities ranged from 1.2 to 0.7 cm cm^{-3} at the same depth and distances for trees on Carrizo rootstock. Root densities decreased for both rootstocks to low values at the 30 to 45 cm depth. Root densities increased for trees on Carrizo at 45 to 60 cm depth, whereas densities for trees on Swingle increased at the 60 to 75 and 75 to 90 cm depths. With the exception of the 50 cm distance from the tree trunk, root densities were greater for trees on Carrizo at 30 to 45 cm than those on Swingle. Likewise, root densities were greater at 45 to 60 cm depth for trees on Carrizo than at the 60 to 75 cm depth for trees on Swingle.

Root Length Density Distribution Changes with Tree Size

Citrus root length densities were significantly different at the P=0.01 level for both distance from the tree trunk and depth from the soil surface across a wide range of tree sizes (Table 4-2). Three-dimensional graphical representations of developing root systems are presented in Fig. 4-3. These graphs represent trees approximately 2 to 5 years old (Figs. 4-3A and 4-3B), 5 to 10 years old (Figs. 4-3C and 4-3D), 10 to 15 years old (Figs. 4-3E), and >15 years old (Figs. 4-3F). Root systems were initially concentrated at the surface with few roots deeper than 0.5 m at a distance of 150 cm from the tree trunk. As the citrus trees produced substantial fruit (5 to 10 years of age) root length density increased at the soil surface to the dripline of the tree. Roots eventually extended to the 200 cm distance between tree rows and to a depth of 0.9 m at 150 cm from the trunk. The bimodal nature of the root system can be seen near the tree at depths below 60 cm. By the time the tree reached 10 to 15 years of age and the canopy was nearing full hedgerow dimensions, the bimodality of the root system was fully developed and roots extended past a depth of 1 meter at all distances from the tree.

Tables 4-3 and 4-4 list the regression coefficients for a third order polynomial relationship of canopy volume and trunk diameter to root length density at all depths and distances. The r^2 values were greater, and RSME and P values were lower for most regressions using canopy volume than those using trunk diameter, indicating that canopy volume measurements are a more accurate predictor for assessing root length density compared with trunk cross sectional area.
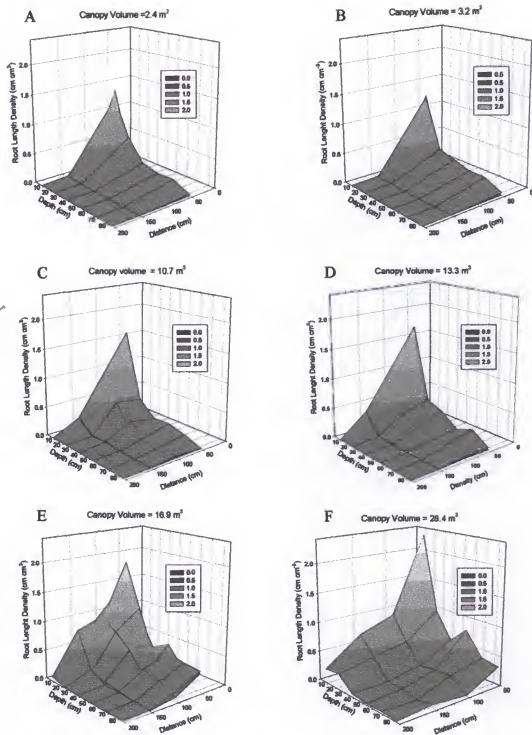
Fig. 4-3. Citrus root distributions by depth below the soil surface and distance from the tree trunk for trees 2-5 years old (A and B), 5-10 years old (C and D), 10-15 years old (E), and > 15 years old (F).

Table 4-2. Regression analysis of citrus fibrous (diameter < 4 mm) root length densities for trees ranging from 2 to > 15 years old.

	RMSE	CV	R^2	P	Significance
Orientation	44.66	87.81	0.002	0.291	NS
Distance	48.08	42.54	0.12	<0.0001	***
Depth	23.45	51.99	0.17	<0.0001	***

Table 4-3. Regression coefficients and statistics root length density as a function of distance from the tree trunk, and soil depths by canopy volume using a third order quadratic polynomial model[z].

Distance (cm)	Depth (cm)	Y_0	a	b	c	R^2	RMSE (cm cm^{-3})	P
50	0-15	1.29	-0.021	0.002	0.00001	0.84	0.33	0.001
50	15-30	0.99	-0.289	0.027	-0.0006	0.78	0.15	0.005
50	30-45	0.27	-0.059	0.006	-0.0001	0.68	0.09	0.021
50	45-60	0.45	-0.16	0.015	-0.00003	0.83	0.12	0.002
50	60-75	0.29	-0.099	0.009	-0.00002	0.68	0.09	0.022
50	75-90	0.31	-0.14	0.013	-0.0003	0.88	0.06	0.0005
100	0-15	0.73	-0.23	0.023	-0.0005	0.79	0.15	0.005
100	15-30	0.44	-0.13	0.014	-0.0003	0.61	0.15	0.072
100	30-45	0.19	-0.069	0.007	-0.00002	0.48	0.14	0.14
100	45-60	0.20	-0.082	0.008	-0.00002	0.82	0.05	0.002
100	60-75	0.071	-0.068	0.006	-0.00001	0.85	0.04	0.001
100	75-90	0.040	-0.018	0.002	-0.00001	0.51	0.04	0.107
150	0-15	0.17	-0.087	0.011	-0.0001	0.97	0.06	<0.0001
150	15-30	0.10	-0.047	0.005	-0.0001	0.81	0.06	0.003
150	30-45	0.007	-0.004	0.001	-0.00001	0.74	0.02	0.010
150	45-60	0.025	-0.012	0.001	-0.00001	0.80	0.03	0.003
150	60-75	0.007	-0.004	0.0004	-0.000001	0.75	0.01	0.008
150	75-90	0.008	-0.004	0.0003	-0.000001	0.65	0.01	0.030
200	0-15	0.042	-0.020	0.002	-0.0001	0.99	0.01	0.014
200	15-30	-0.013	0.007	-0.001	0.0001	0.99	0.01	<0.0001
200	30-45	-0.0003	0.001	-0.0001	0.00001	0.99	0.01	<0.0001
200	45-60	-0.002	-0.001	0.0001	0.00001	0.99	0.01	0.004
200	60-75	0.003	-0.001	0.0001	-0.00001	0.99	0.01	0.004
200	75-90	-0.001	0.001	-0.0001	0.00001	0.99	0.01	0.0002

[z] $Y=Y_0+aX+bX^2+cX^3$ where $X = TCV$, and Y_0, a, b, and c are regression coefficient.

Table 4-4. Regression coefficients and statistics for root length density as a function of distance from the tree trunk, and soil depths by trunk cross-section area using a third order quadratic polynomial model[z].

Distance (cm)	Depth (cm)	Y_0	A	b	c	R^2	RMSE (cm cm^{-3})	P
50	0-15	-0.41	0.001	-0.00005	0.00001	0.71	0.44	0.015
50	15-30	0.24	0.0001	-0.00003	0.00001	0.56	0.21	0.071
50	30-45	0.04	0.0001	-0.00001	0.00001	0.68	0.09	0.022
50	45-60	-0.50	0.0005	-0.00006	0.00003	0.88	0.10	0.001
50	60-75	-0.08	0.0001	-0.00002	0.00002	0.66	0.09	0.027
50	75-90	-0.20	0.0002	-0.00003	0.00001	0.79	0.08	0.004
100	0-15	0.23	0.00001	-0.00001	0.00001	0.67	0.19	0.026
100	15-30	-0.01	0.0001	-0.00001	0.00001	0.36	0.19	0.343
100	30-45	-0.42	0.0004	-0.00003	0.00002	0.52	0.13	0.099
100	45-60	-0.17	0.0002	-0.00002	0.00002	0.82	0.05	0.003
100	60-75	-0.15	0.0002	-0.00002	0.00001	0.90	0.03	0.0002
100	75-90	-0.20	0.0002	-0.00001	0.00001	0.97	0.01	<0.0001
150	0-15	-0.50	0.0004	-0.00001	0.00002	0.96	0.07	<0.0001
150	15-30	-0.30	0.0003	-0.00003	0.00001	0.83	0.06	0.002
150	30-45	-0.11	0.0001	-0.00001	0.00001	0.83	0.02	0.002
150	45-60	-0.15	0.0001	-0.00001	0.00001	0.78	0.03	0.005
150	60-75	-0.01	0.00001	-0.00001	0.00001	0.74	0.01	0.010
150	75-90	-0.05	0.00001	-0.00005	0.00001	0.61	0.02	0.046
200	0-15	-0.28	0.0002	0.00003	0.00001	0.94	0.04	0.086
200	15-30	-0.33	0.0003	-0.00003	0.00001	0.78	0.08	0.311
200	30-45	-0.07	0.0001	-0.00001	0.00001	0.80	0.02	0.282
200	45-60	-0.03	0.00001	-0.00003	0.00001	0.87	0.01	0.192
200	60-75	-0.04	0.00001	-0.00004	0.00001	0.88	0.01	0.180
200	75-90	-0.03	0.00001	-0.00002	0.00001	0.79	0.01	0.293

[z] $Y = Y_0 + aX + bX^2 + cX^3$ where X = TXA, and Y_0, a, b, and c are regression coefficients

Discussion

The root distributions of the two rootstocks used in this study appear to lie intermediate between the extensive and intensive distributions described by Castle and Krezdorn (1975). However, there were some subtle differences between rootstocks. Citrus trees grown on Swingle citrumelo had greater root length densities in the upper 30 cm than did trees grown on Carrizo citrange. The root density distributions of both rootstocks were bimodal in nature. However, Carrizo roots tended to grow deeper than did those of Swingle. Trees grown on Carrizo citrange rootstock had higher fibrous root length densities at all distances from the tree trunk below 60 cm from the soil surface. These root length densities indicate that the depth of irrigation and the depth to which fertilizer N is initially placed should be rootstock specific. Thus, mature trees grown on Swingle citrumelo should be irrigated to a shallower depth compared with trees grown on Carrizo citrange. Deep irrigation will waste water and potentially leach soil N below the soil volume containing the largest proportion of roots, thus potentially decreasing NUE.

Menocal-Barberena (2000) found similar trends using fibrous root mass densities from root samples collected at the same site. In his and the current studies, Swingle had greater, but not significantly different, fibrous root concentrations than Carrizo. Mean in-row root concentrations were significantly greater than between-row concentrations. Mean root concentrations in the upper 30 cm were more than four times greater than for soil layers below the 30 cm depth.

Under central Florida "Ridge" conditions, citrus fibrous root densities increase in two modes. The first mode is the development of a dense root mat just below the soil surface. This portion of the root system expands in radial manner away from the tree

trunk while continuing to increase in density near the trunk itself. Expansion continues through maturity with trees in dense plantings overlapping in both in-row and between-row directions. This portion of the citrus root system is important for tree stability while providing adequate roots for water and nutrient uptake for the developing tree. A second region of root growth develops below 30 cm between 5 and 10 years of age. This region of root growth increases in size and density through maturity. The development of a deeper root system is essential for supplying adequate water and nutrients to the mature tree from an increasingly large soil volume. These two growth modes result in the bimodal root distribution of the mature citrus tree. While complex, the development of citrus root systems with time appears to be predictable and basic trends can be captured in functional relationships within a citrus model. The data presented here can provide the root distribution information needed to determine spatial soil water and nutrient uptake for a citrus growth model.

Conclusions

It is concluded that the root length distribution of trees grown on Swingle and Carrizo rootstocks followed predictable patterns with increased tree size resulting in mature trees with bimodal root systems. While both rootstocks developed a dense root system within the upper 30 cm of the soil surface, the root systems extended beyond 1 m in depth, so extending sampling to greater soil depths on well-drained soils appears to be desirable. Trees on Swingle developed higher root length densities near the soil surface, and lower densities below 30 cm compared with trees on Carrizo. Based on the overall high r^2 values and low RMSE, the functional relationships that were developed in this study account for most of the variability in root length density. Thus, the test hypothesis

is correct and a model for root length density distribution can be made if both tree size and rootstock are included as variables. These relationships provide a scientific basis for the development of a spatial root length distribution model needed for a citrus expert system that will estimate water and nutrient uptake.

CHAPTER 5
CITRUS WATER UPTAKE DYNAMICS

Introduction

Climate, crop development, soil water status, and competition with other plants affect total soil water use by crop plants. Stomatal conductance regulates both transpiration and photosynthesis and therefore directly affects the water use and productivity of plants (Jones et. al., 1985). Stomata are sensitive to environmental variables such as light, CO_2, vapor pressure deficit (VPD), and plant water status (Jarvis and McNaughton, 1986). Assuming that light, CO_2, and VPD conditions are nearly constant during short intervals of time, hourly and daily changes in plant water status can have large impacts on stomatal conductance and thus on transpiration rates and ultimately productivity. The key to plant water status is soil water availability (Allen et al., 1997), thus an improved understanding of soil water uptake dynamics is essential in optimizing both the amount and timing of irrigation required for maximum production. Once understood, seasonal soil water content and root length density effects on citrus water uptake can be modeled to provide more accurate irrigation scheduling, which will reduce negative impacts on ground water quantity and quality due to leaching and over-pumping.

Citrus water requirements vary with climatic conditions, variety, and canopy size. Lower crop evapotranspiration (ET_c) rates for Florida (humid) compared with Arizona (semi-arid) have been attributed to lower evaporative demand (Rogers et al. 1983, Fares

and Alva 1999). Rogers and Bartholic (1976) determined that annual ET_c increased at a rate of 19 mm per year as trees grew, leading to a cumulative increase of approximately 13% in an 8–year period.

Soil water content can also be reduced by evaporation from the soil surface and transpiration from non-crop species (Allen et al., 1998). Generally, soils lose the ability to transport water to the surface as they dry (Hillel, 1998). Citrus ET_c decreases as the fraction of the soil surface receiving full sun decreases and the canopy shades an increasingly larger ground area (Castel and Buj, 1992). Soil water use or apparent ET_c increases with increased ground coverage by non-crop species (Smajstrla et al., 1986).

The above factors combine to limit ET for a given crop under given conditions. Allen et al. (1998) proposed that ET_c can be derived from calculated ET_o as follows:

$$ET_c = ET_o * K_c * K_s \qquad\qquad \text{Equation 5-1}$$

Where:

ET_c = Crop evapotranspiration (mm d^{-1})

ET_o = Potential evapotranspiration (mm d^{-1})

K_c = Crop coefficient

K_s = Soil stress coefficient

The crop coefficient (K_c) is defined as the ratio of ET_c to ET_o at field capacity (θ_{FC}). In this case K_s is assumed to be equal to unity. This coefficient is indicative of climatic and/or developmental effects on ET_c compared with ET_o when water uptake is not limited by soil water depletion. Estimates of K_c for citrus range from a minimum of 0.6 in the fall and winter to a maximum of 1.2 during the summer months (Boman, 1994; Fares and Alva, 1999; Martin et al., 1997; Rogers et al., 1983).

Soil water content (θ) must be maintained between specific upper and lower limits such that water availability to the crop does not limit growth or adversely impact yield or quality. This upper limit of θ after free drainage occurs is defined as the value of θ at which redistribution of soil water ceases (Hillel, 1998) and is also known as field capacity (θ_{FC}). The lower limit or permanent wilting point (θ_{PWP}) is the value for θ at which a wilted plant can no longer recover turgidity. The range of θ between θ_{FC} and θ_{PWP} is known as total available water (TAW). These three values for θ and the soil water potential (ϕ) at which they occur are characteristic and relatively constant for any given soil. If the effects of soil physical characteristics on soil water use are understood, soil water can be maintained within these limits and the potential for both crop water stress and environmental contamination can be minimized.

The soil water depletion coefficient (K_s) in equation 5-1 is a measure of the reduction in ET_c caused by reduced soil water uptake due to reduced ϕ (Allen et al., 1998). Water moves to regions of high ϕ from regions of lower ϕ as water is removed from the soil surrounding the root surface. Soil water movement slows as ϕ of the bulk soil decreases and θ approaches θ_{PWP}. Allen et al. (1997) determined that a θ exists (θ_{RA}) less than θ_{FC} where water uptake was not limited by ϕ. They referred to the range of θ to θ_{RA} as readily available water (RAW) and used this value to estimate K_s as the ratio of depletion of total available soil water (TAW-θ) to the soil water not readily available (TAW-RAW) where K_s is not greater than unity (Equation 5-2). Therefore, the greater the RAW for a given soil, the longer water can be withdrawn from that soil before ET_c is limited. A crop and specific depletion in TAW must be determined below which crop growth and yield is reduced. Under Florida conditions, Koo(1963) estimated this

delpetion in TAW to be 33% from February to June and 66% from July to January. These
values were determined for relatively low density plantings with overhead irrigation. The
depletion amounts for high density plantings irrigated with under-tree low volume
mircrosprinklers have not been determined.

$$K_s = \frac{TAW - \theta}{TAW - RAW}$$

Equation 5-2

Where:

Ks = Soil water stress coefficient

TAW = θ_{FC} - θ_{PWP} = Total available water (cm^3 cm^{-3})

θ = Soil water content (cm^3 cm^{-3})

RAW = θ_{FC} - θ_{RA} = Readily available water (cm^3 cm^{-3})

The hypotheses to be tested for the following study on citrus soil water dynamics
are: 1) seasonal changes in maximum daily water uptake under non-limiting soil water
conditions follows predictable patterns relative to ET$_o$, 2) water uptake decreases with
soil water content, and 3) soil water uptake is greatest in soil volumes containing the
highest root length densities. The objectives of this study were to: 1) estimate mature tree
daily ET$_c$ during a 2-year period, 2) calculate monthly K$_c$ values based on the relationship
K$_c$ = ET$_c$ / (ET$_o$*K$_s$), 3) determine the relationship of estimated ET$_c$ to soil water content
to determine K$_s$ values over a range of ϕ, and 4) evaluate ET$_c$ per unit root length density.
The resulting relationships will provide critical information required for the development
of predictive models for citrus water uptake and soil water depletion over time. Such
models can provide a basis to protect Florida's water resources though better irrigation
scheduling and appropriate water application rates.

Materials and Methods

Site Characteristics

'Hamlin' orange (*Citrus sinensis* L.) grafted on Carrizo citrange (*C. sinensis* L. Osbeck X *Poncirus trifoliata* L. Raf.) rootstock trees planted 3.1 m in the row and 6.1 m between rows (used in Experiment 1 of Chapter 3) were used in this study. The trees had been pruned each of the past 3 years and had formed a hedgerow approximately 3.8 m wide and 5.9 m tall. Herbicides were applied as needed to maintain a nearly weed-free strip 3.5 to 4.0 m wide beneath the tree canopies. Soil type at the site was Candler fine sand (hyperthermic, uncoated Typic Quartzipsamments) with a field capacity of approximately 0.08 cm^3 cm^{-3} (Obreza et al., 1997). Irrigation was applied to the tree row using one microsprinkler per tree with a flow rate of approximately 60.5 L hr^{-1} and a 360 degree spray pattern with a diameter of approximately 3.7 m. The equivalent mean precipitation rate of the sprinkler was 0.58 cm hr^{-1}. Reclaimed municipal-waste water provided by the Water Conserv II Project was used as the source of irrigation water.

Soil Capacitance Sensor Data Collection

Soil water content at 10, 20, 40, and 80 cm depths was recorded at 30 minute intervals during a 2-year period in the irrigated and non-irrigated areas under three mature (14-year-old) citrus trees. These increments represent soil depths of 0 to 15, 15 to 30, 30 to 60, and 60 to 100 cm, respectively (Fig.5-1). These θ data were obtained using EnviroSCAN (Sentek Pty. Ltd., South Australia) capacitance sensors installed two distances away from the tree trunk in the row and three distances perpendicular to the row (Fig.5-2). In-row sensors were placed 0.75 m from the tree trunk and at the midpoint
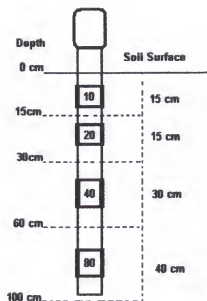
Fig. 5.1. Illustration of EnviroSCAN probe. Number on sensor indicates depth of sensor.
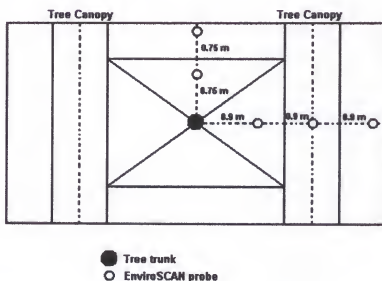
Fig. 5-2. Illustration of EnviroSCAN probe layout, and soil surface area used for determining soil water content for each probe.

between trees (1.5 m). Between row sensors were installed midway between the tree trunk and the canopy dripline (0.9 m), the canopy dripline (1.8 m), and between the dripline and midline between tree rows (2.7 m).

Access tubes (5 cm diameter, acrylonitrile butadiene styrene) were installed, and each sensor was individually normalized following manufacturer recommendations. A general calibration curve was developed for the soil type at the site using a gravimetric method described by Morgan et al. (1999). Daily Penman ET_o values from a Florida Automated Weather Network (FAWN) station located less than 0.4 km away from the actual field site were recorded.

Estimated Daily ET_c

Soil water content in deep sandy soils equilibrates to field capacity within a few hours after irrigation or rainfall. The net change in θ over a 24 hour period was calculated for each sensor using the difference between θ values recorded at midnight and values recorded the previous midnight ($\Delta\theta$). To avoid hysterisis effects, only θ data collected on days receiving no rainfall or irrigation were used for this calculation. Daily soil water depletion depth was calculated for each sensor by multiplying the $\Delta\theta$ by a corresponding soil depth for that sensor (Fig. 5-1). The resulting soil water depths were then multiplied by the surface area assigned to the given probe (Fig. 5-2). The resulting soil water depletion volumes were summed as an estimate of daily soil water depletion (DSWD). Daily ET_c was estimated by dividing DSWD by the area occupied by the tree (18 m^2). Available soil water and daily weighted θ were determined using the same mehod as that of DSWD by substituting θ_{FC} and mean daily θ for $\Delta\theta$. Mean daily ϕ was estimated from the daily weighted θ using the soil water characteristic curve for Candler fine sand

previously determined at this site (Obreza et al., 1997). Percentage daily ASWD was
determined using DSWD and ASW. $ETc \rightarrow ET_o \cdot Kc_c \cdot Ks$
                                                                    Kc

Estimated Monthly Crop Coefficient (K_c)

Estimated daily tree water use (ET_c) was calculated for a 24-month period and
compared with calculated daily ET_o. The ratios of estimated daily ET_c to calculated daily
ET_o for each of the three trees were averaged to estimate the product $K_c * K_s$ in equation
5-1. To eliminate the effects of decreased ϕ on water uptake, ratios of ET_c to ET_o on days
where mean θ was near θ_{FC} in both the irrigated and non-irrigated areas (K_s assumed to
be 1) were used to estimate daily K_c. The relationship of these estimated daily K_c values
to day of year (DOY) was determined using regression analysis.

Estimated Water Stress Coefficient (Ks)

Daily ET_c to ET_o ratios were calculated throughout the year and compared with
mean daily θ. The ratio of ET_c to ($ET_o * K_c$) using the K_c estimated for the day was used to
estimate the value of K_s. The relationship of the ratio of ET_c to ($ET_o * K_c$) with θ and ϕ is
typically a logistic response curve with a plateau near θ_{FC} (Allen et al., 1998). Regression
analysis was used to determine the relationship of estimated K_s to ASWD and mean soil
ϕ.

Estimation of Soil Water Uptake per Unit Root Length

Daily estimated ET_c on a per unit root length basis for each sensor were
determined for the mean under-canopy, dripline, and between-row locations for soil
depths of 10, 20, 40 and 80 cm. Root length densities determined in Chapter 4 (for trees
on the same rootstock, same approximate tree size, and grown in the same location under

the same irrigation and fertilization practices) were used as an approximation of root length desities at the various locations and depths.

The rate of soil water withdrawal is influenced by surface evaporation and is related to the amount of soil shading. Likewise, transpiration by groundcover species increases withdrawal. Water withdrawal rates per unit root length at all locations and depths were compared. Increased water loss at the soil surface that could not be explained by root density was assumed to be due to one or both of the above factors.

Results

Seasonal ET_o and ET_c Trends

Daily ET_o reported by FAWN for the experimental site ranged from a minimum of 1.1 mm in December, 2001 to a maximum of 6.5 mm in June, 2000 (Table 5-1). The standard deviations for ET_o by month were relatively low (<0.4 mm) for all months with the exception of transition months between seasons (February and March in the spring and August and September in the fall). This result indicates that weather condtions related to ET_o were relatively stable with the exception of these transition periods. Monthly maximum, minumum, and mean values for ET_o and ET_c were not significantly different for corresponding months during the 2 years of observations included in this study. Although generally lower, daily ET_c followed the same seasonal patterns as ET_o. Exceptions to this trend occurred during the summer months of June through August, but

Table 5-1. Monthly maximum, minimum, and mean reference evapotranspiration reported by Florida Automated Weather Network for the Avalon Station and maximum, minimum and mean estimated citrus crop evapotranspiration.

Months	Reference Evapotranspiration (mm d^{-1})				Crop Evapotranspiration (mm d^{-1})			
	Maximum	Minimum	Mean	Standard Deviation	Maximum	Minimum	Mean	Standard Deviation
April 2000	5.0	4.0	4.5	0.31	4.7	3.1	3.9	0.54
May	5.9	4.1	5.0	0.46	5.9	3.9	4.6	0.57
June	6.5	5.0	5.7	0.44	6.5	3.5	4.7	0.72
July	5.8	4.6	5.3	0.35	5.8	3.5	4.6	0.72
August	5.2	4.1	4.7	0.33	5.4	3.0	4.2	0.66
September	5.0	3.3	4.3	0.48	4.8	2.5	3.5	0.70
October	3.8	2.3	3.0	0.38	2.7	1.7	2.2	0.32
November	2.9	1.6	2.3	0.39	2.2	1.3	1.8	0.26
December	2.8	1.5	1.9	0.31	1.9	1.0	1.3	0.24
January, 2001	2.9	1.3	2.0	0.45	2.1	1.0	1.4	0.26
February	3.6	1.2	2.7	0.70	2.6	1.4	1.8	0.29
March	4.3	2.6	3.5	0.38	3.1	2.0	2.8	0.28
April	5.0	3.3	4.5	0.36	5.2	2.5	4.0	0.68
May	5.9	3.6	5.3	0.52	6.2	3.9	4.3	0.60
June	6.4	4.9	5.6	0.35	6.3	3.5	4.8	0.91
July	6.2	5.1	5.5	0.28	6.3	3.6	4.5	0.53
August	6.2	4.6	5.3	0.44	5.9	2.7	4.5	0.63
September	5.5	3.4	4.5	0.62	4.8	1.9	3.4	1.01
October	3.6	2.2	2.9	0.39	3.0	1.5	2.0	0.38
November	2.7	1.4	2.1	0.31	2.8	1.6	1.4	0.47
December	2.2	1.1	1.8	0.27	1.8	1.1	1.3	0.31
January, 2002	3.0	1.2	2.0	0.58	1.9	1.2	1.4	0.22
February	3.2	1.9	2.6	0.29	2.3	1.3	1.9	0.34
March	4.4	2.1	3.6	0.56	3.4	1.6	2.9	0.55
April	5.3	3.3	4.3	0.60	4.6	1.7	3.2	0.74
				Statistical Significance[z]				
Month	NS	NS	NS	NS	NS	NS	NS	NS

[z] NS = Not significantly different by General linear Model at the p=0.05 level.

Seasonal K_c*K_s

The ratio of estimated daily ET_c to calculated daily ET_o is an approximation of the

quantity K_c*K_s in Equation 5-1. The ET_c to ET_o ratios (= K_c*K_s) were plotted against the

weighted θ, ASWD, and ϕ for the irrigated area to depths of 0.5 and 1 m, or for the total

land area allocated to the tree area to a 1 m depth (Figs. 5-3 to 5-5). Regression equations,

R^2, RMSE, and P values are provided in Table 5-2. The R^2 values for the equations are

generally smaller than 0.5 due to the wide scatter of data points as indicated by the

relatively large RMSE values. However, all relationships were significant at the P=0.01

level. The trends were particularly strong for regressions against soil water potential.

Theoretically, the K_s value should be approximately 1 when θ is near θ_{FC} (0.075

to 0.08 cm³ cm⁻³). Therefore, the ET_c to ET_o ratios should approximate K_c at θ_{FC}. Fig. 5-

6 illustrates the ET_c to ET_o ratios by day of year (DOY) when mean θ in the irrigated

zone was between 0.07 and 0.085 cm³ cm⁻³ to a depth of 1 m. These ratios ranged from

0.81 on DOY 24 (January) to 1.12 on DOY 179 (June). The regression equation for this

relationship is given in Table 5-3. With an R^2 of 0.76, DOY explains more than 76% of

the variation in the ET_c to ET_o ratios when θ was between 0.07 and 0.085 cm³ cm⁻³.

Therefore, the equation provides a good approximation of the value of K_c for a given

DOY.

K_s Estimation

The ET_c to ET_o ratios for θ values less than θ_{FC} would approximate the K_s value

assuming the K_c is 1. Since we have demonstrated that K_c values do not equal 1 during
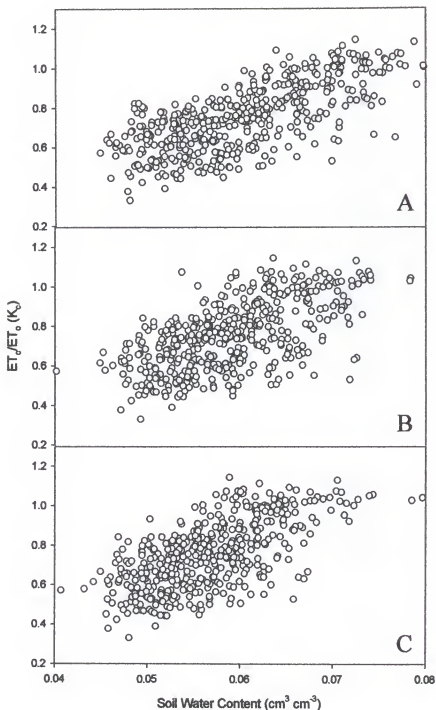
Fig. 5-3. Estimated ET_c to calculated ET_o ratio as a function of soil water content in the irrigated zone to a 0.5 m depth (A), 1 m depth (B), and the total tree area to a 1 m depth (C). The data points shown represent a range of soil water content from field capacity to approximately 50% available soil water depletion.
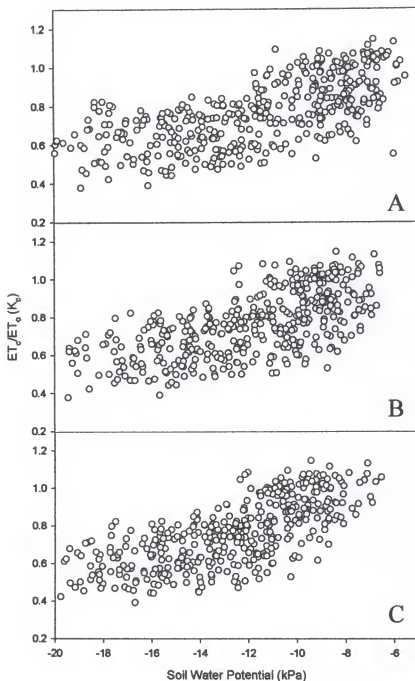
Fig. 5-4. Estimated ET_c to calculated ET_o ratio as a function of soil water potential in the irrigated zone to a 0.5 m depth (A), 1 m depth (B), and the total tree area to a 1 m depth (C). The data points shown represent a range of soil water content from field capacity to approximately 50% available soil water depletion.
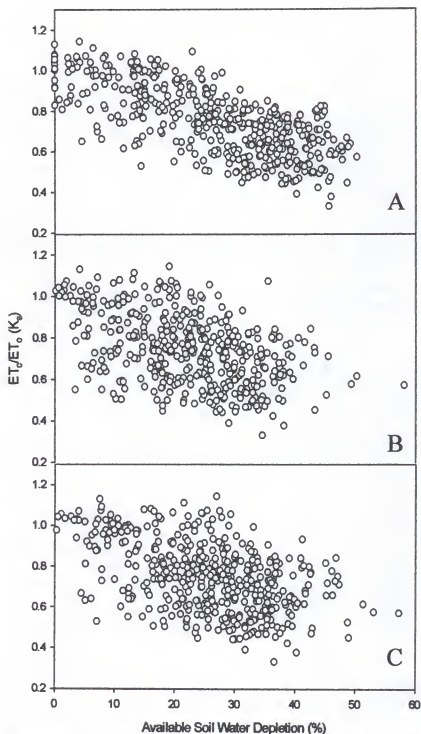
Fig. 5-5. Estimated ET_c to calculated ET_o ratio as a function of available soil water depletion in the irrigated zone to a 0.5 m depth (A), 1 m depth (B), and the total tree area to a 1 m depth (C). The data points shown represent a range of soil water content from field capacity to approximately 50% available soil water depletion.

Table 5-2. Regression analysis of estimated ET_c to calculated ET_o ratio by mean soil water content, soil water potential, and available soil water depletion in the upper 0.5 and 1.0 m of soil for either the irrigated zone or total allocated tree area.

Soil Water Content – Cubic Function[z]						
	Y_0	a	b	c	R^2	RMSE	P
0.5 m irrigated	8.32	-398.0	6626	-35004	0.52	0.12	<0.0001
1 m irrigated	3.02	-145.6	2695	-14903	0.36	0.14	<0.0001
1 m total	4.15	-209.6	3876	-21806	0.42	0.13	<0.0001

Soil Water Potential – Exponential Decay Function[y]						
	Y_0	a	b	R^2	RMSE	P
0.5 m irrigated	0.51	1.12	0.14	0.44	0.13	<0.0001
1 m irrigated	0.41	1.16	0.11	0.38	0.13	<0.0001
1 m total	0.37	1.33	0.10	0.46	0.13	<0.0001

Available Soil Water Depletion – Logistic Function[x]						
	Y_0	X_0	A	B	R^2	RMSE	P
0.5 m irrigated	0.55	26.06	0.40	3.44	0.51	0.12	<0.0001
1 m irrigated	0.02	81.10	0.93	0.92	0.25	0.15	<0.0001
1 m total	0.34	34.70	0.69	1.09	0.27	0.15	<0.0001

[z] $Y = Y_0 + aX + bX^2 + cX^3$ where $X = ET_c/ET_o$, and Y_0, a, b, and c are regression coefficients

[y] $Y = Y_0 + a\exp^{-bX}$ where $X = ET_c/ET_o$, and Y_0, a, and b are regression coefficients

[x] $Y = Y_0 + \dfrac{a}{1 + \left(\dfrac{X}{X_0}\right)^b}$ where $X = ET_c/ET_o$, and Y_0 a, and b are regression coefficients
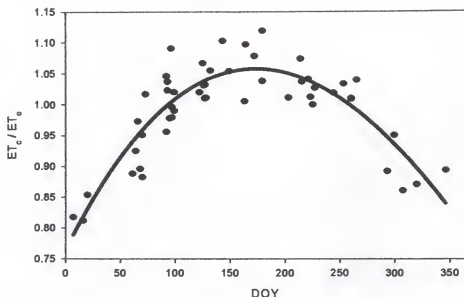
Fig. 5-6. Comparison of estimated crop evapotranspiration (ET_c) with calculated reference evapotranspiration (ET_o) ratio. This value represents an approximation of K_c for observations when soil water content values were near field capacity. Kc values are expressed as a function of day of year (DOY).

Table 5-3. Regression analysis of estimated ET_c to calculated ET_o ratio by day of year for soil water content values greater than 0.070 cm^3 cm^{-3} (field capacity) using a quadratic function[Z].

	Y_0	a	b	R^2	RMSE	P
DOY	0.71	0.004	-0.00001	0.76	0.056	<0.0001

[Z] $Y = Y_0 + aX + bX^2$ where $X = ET_c/ET_o$, and Y_0 a, and b are regression coefficients

the course of a season, daily ET_c values were multiplied by the appropriate K_c value estimated for the DOY. $ET_c * K_c$ to ET_o ratios were then calculated to approximate K_s and were plotted against ASWD and ϕ (Figs. 5-7 and 5-8). Lines indicating estimations of K_s using equation 5-2 and 15% depletion as an estimate for RAW are included in Figs. 5-7 and 5-8. Estimated Ks values based on ASWD are presented in Table 5-4. Table 5-5 shows higher R^2 values and lower RMSE values compared with ET_c to ET_o ratio
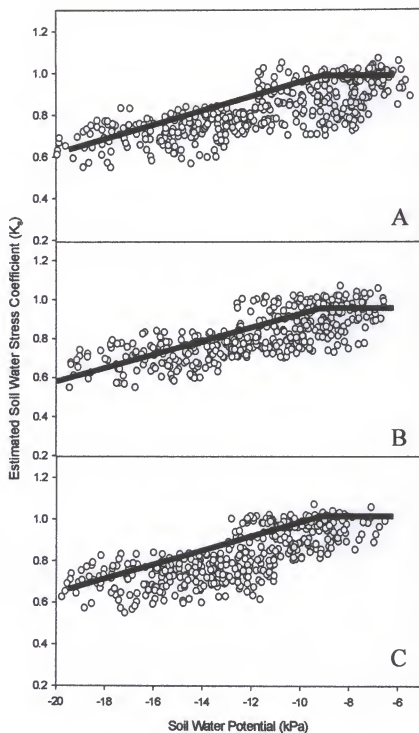
Fig. 5-7. Estimated soil water stress coefficient K_s as a function of soil water potential in the irrigated zone to a 0.5 m depth (A), 1 m depth (B), and the total tree area to a 1 m depth (C). The data points shown represent a range of soil water content from field capacity to approximately 50% available soil water depletion.
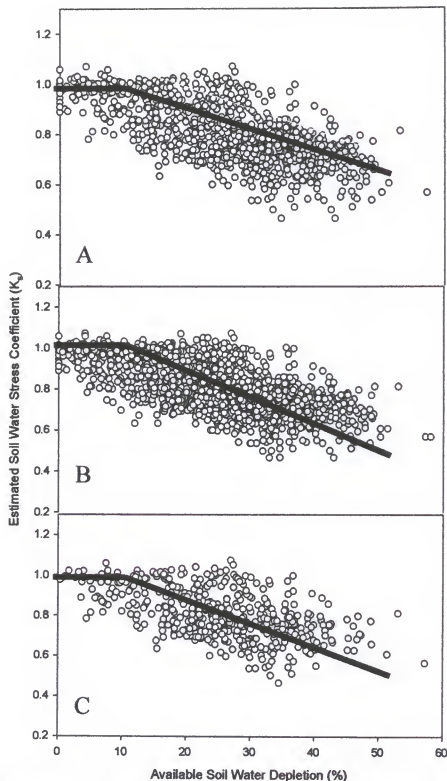
Fig. 5-8. Estimated soil water stress coefficient K_s as a function of available soil water depletion in the irrigated zone to a 0.5 m depth (A), 1 m depth (B), and the total tree area to a 1 m depth (C). The data points shown represent a range of soil water content from field capacity to approximately 50% available soil water depletion.

Table 5-4. Estimated soil water coefficient (K_s) values for a range of percentage available soil water depletion (ASWD) using Equation 2 as reported by Allen et al., (1997). A value of 15% ASWD is used for RAW, therefore estimated K_s for ASWD less than 15% are assumed to equal 1.0.

ASWD (%)	Estimated K_s
0	1.00
10	1.00
20	0.94
30	0.82
40	0.71
50	0.59
60	0.47
70	0.35
80	0.24
90	0.12
100	0.00

Table 5-5. Regression analysis of estimated soil depletion factor (K_s) by mean soil water potential, and available soil water depletion in soil 0.5 or 1.0 m deep and in either the irrigated zone or total tree area.

Soil Water Potential – Logistic Function[z]							
	Y_0	X_0	a	b	R^2	RSME	P
0.5 m irrigated	0.58	11.50	0.44	2.97	0.53	0.086	<0.0001
1 m irrigated	0.61	11.49	0.41	3.66	0.47	0.091	<0.0001
1 m total	0.65	12.25	0.34	5.11	0.47	0.091	<0.0001
Available Soil Water Depletion – Logistic Function[z]							
	Y_0	X_0	a	b	R^2	RMSE	P
0.5 m irrigated	0.40	42.37	0.58	1.98	0.63	0.076	<0.0001
1 m irrigated	0.48	34.85	0.48	1.55	0.39	0.097	<0.0001
1 m total	0.60	28.70	0.38	1.86	0.32	0.103	<0.0001

[z] $Y = Y_0 + \dfrac{a}{1 + \left(\dfrac{X}{X_0}\right)^b}$ where $X = K_s$, and Y_0 a, and b are regression coefficients

equations presented in Table 5-2. RMSE values in Table 5-4 were generally 25% lower than those in Table 5-2. The R^2 values were greater for equations made using ASWD and ϕ in the irrigated zone to a depth of 0.5 m compared with those using the irrigated area and total tree area to a 1 m depth. This result indicates that the soil volume with greater root length densities dried out faster resulting in better correlation of K_s with both ASWD and ϕ. Estimated values for K_s are approximately 1 at θ_{FC}.

Soil Water Uptake per Unit Root Length

Equations resulting from regression analysis of soil water uptake per unit root length density against mean daily ϕ are presented in Table 5-6. An exponential decay model typically resulted in the best fit. Water uptake per unit root length values were remarkably similar for the various locations and depths, with the exceptions of the 10 cm depth between-rows and the 40 and 80 cm depths at the dripline. Maximum water uptake per unit root length of 0.4 mm^3 cm^{-1} d^{-1} occured at θ_{FC} or approximately -5 kPa. Water uptake per unit root length decreased rapidly as ϕ decreased to approximately -12 or -13 kPa, then gradually decreased from 0.1 to 0.05 mm^3 d^{-1} cm^{-1} as ϕ decreased below -20 kPa. A wide scatter in the data along with a long shallow sloping tail resulted in a relatively low R^2 and generally high RMSE values. However, all regressions were significant at the P=0.01 level and formed an approximation of water uptake at given bulk ϕ within the constratints of the RMSE.

Water uptake per unit root length values of approximately 0.8 mm d^{-1} cm^{-1} at θ_{FC} were found at the 10 cm depth between-rows. This value is double that at other locations and depths (data not shown). The increase in water uptake could be explained by water

Table 5-6. Regression analysis of estimated soil water uptake per unit root length density on soil water potential in soil at three locations and for the 10, 20, 40 or 80 cm depths using an exponential decay model[z].

Location	Depth (cm)	Y_0	a	b	R^2	RMSE (mm d^{-1} cm^{-1})	P
Under-Canopy	10	0.07	1.08	0.29	0.23	0.14	<0.0001
	20	0.43	-0.29	0.05	0.13	0.35	0.0895
	40	0.22	15.46	0.50	0.30	0.28	<0.0001
	80	0.25	71.70	0.98	0.14	0.30	<0.0001
Dripline	10	0.16	7.89	0.49	0.20	0.26	<0.0001
	20	0.14	4.69	0.36	0.24	0.36	<0.0001
	40	0.60	4.74	0.15	0.62	0.24	<0.0001
	80	0.33	40.75	0.61	0.29	0.30	<0.0001
Between-Rows	10	0.04	1.24	0.08	0.22	0.33	<0.0001
	20	0.14	5.28	0.33	0.20	0.33	<0.0001
	40	0.03	9.03	0.39	0.35	0.24	<0.0001
	80	0.21	13.74	0.30	0.18	0.52	0.0730

[z] $Y = Y_0 + a\,exp^{-bX}$ where X = root length density, and Y_0 a, and b are regression coefficients

use from non-crop species in the row middles that were not present beneath the tree canopy. However, there was also elevated water use at the 40 and 80 cm depths at the dripline. These data are assumed to be the result of higher than expected root length densities at these depths compared with mean root length density data from similar trees. Therefore, the higher than expected water use per root length at the soil surface between rows could be a combination of both greater root densities and water use by weed and grass species.

Discussion

Citrus water uptake followed relatevely consistent patterns during the 2 years of this study. Daily water withdrawals from the soil followed daily calculated ET_o, with higher values occuring during the summer and lower ones in winter. ET_c values were consistently lower than ET_o except during summer months when θ was near θ_{FC}. These

trends follow reported ET_c values for citrus under both humid and arid climatic conditions (Boman, 1994; Castel et al., 1987; Doorenbos and Pruitt, 1977; Martin et al., 1997; and Rogers et al., 1983). Reported K_c values for central Florida ranged from approximately 0.6 in the winter to 1.1 in summer (Boman, 1994; Fares and Alva, 1999; Rogers et. al., 1983). Estimated mean daily K_c values ranged from 0.55 to 1.2 for citrus under semi-arid to arid conditions (Doorenbos and Pruitt, 1977; Hoffman et al., 1982; Martin et al., 1997; and Wiegand et al., 1982). Thus, seasonal mean ET_c to ET_o ratios reported for this study fall in the range of values documented in the literature.

Allen et al. (1997) refered to estimated K_c values from soil water content measured several days apart as time-averaged K_c and stated that these values are affected by the evaporative power of the atmosphere. They further stated that the higher the evaporative power of the atmosphere, the faster the soil will dry between water applications, and the smaller the time-averaged K_c will be. The reduction in ET_c with lower θ and ϕ reflected by K_s decreasing from 1 to 0.6 as ASWD increased from 10 to 50% seems rather extreme. However, Rogers et al. (1983) suggested that lower estimated K_c values in the spring were caused by low rainfall and low θ outside the irrigated zone. Their reported K_c values of 0.77, 0.72, and 0.95 for March, April and May are 81.3, 71.3, and 89.6% of the K_c values estimated using the regression equation in Table 5-3. Estimated K_c during the rainy season months of June and July were 101.8 and 92.2% of calculated values using the same equation, indicating that K_c values esimated from monthly water balances can lead to lower estimates of K_c during periods of little rainfall and high evaporative demand.

Allen et al.(1997) indicated that a region of readily available water exists between θ_{FC} and approximately 30 to 50% ASWD for loam and loamy clay soils where there is essentially no stress to the crop. This estimate is considerably reduced, however, in the case of citrus on very sandy soils and may only amount to 10 to 15% of ASWD. Estimates for K_s using equation 5-2 closely approximate measured K_s values presented in Fig. 5-5. It is therefore concluded that K_s decreased to approximately 0.6 at 50% ASWD, which translates to a reduction of 40% in ET_c between field capacity and 50% ASWD. Koo (1963, 1978) determined that stress associated with soil water depletion greater than 33% during periods of bloom, fruit set, and rapid vegetative growth in the spring months can reduce potential yield, while depletions of 66% can be tolerated during sumer, fall and winter months. Thus, crop stress associated with K_s values of 0.8 and 0.4 should be used for irrigation scheduling from February through June and from June through January, respectively, to maximize yields while minimizing water use.

Zaongo et al. (1994) reported close correlations beween water uptake and root length density in millet and grain sorghum. Bland and Dugas (1989) estimated maximum water uptake of cotton to be approximately 5 mm^3 d^{-1} cm^{-1} root. Hamblin and Tennqant (1987) found that mean water uptake of cereals and grain legumes was less than 1 mm^3 d^{-1} cm^{-1}. Thus, soil water uptake per unit root length of 0.1 to 0.4 mm^3 d^{-1} cm^{-1} root observed for citrus in this study are similar to published values for other crops, which is somewhat surprising considering the differences in root morphology of annual versus perennial crops. Soil water uptake rates were closely related to root length densities, thus soil regions containing higher root length densities will dry out at a proportionally higher

rate. Hence, a model of soil water uptake and depletion based on root length densities would be appropriate for citrus.

The test hypotheses established for this experiment relating water uptake to time of year, soil water content, and root density has been confirmed. A model based on the concepts of K_c and K_a to estimate daily citrus water uptake is reasonable. The estimation of soil water uptake and resulting depletion based on root length density is sound and would provide a reasonable soil water balance for a nutrient management expert system.

Conclusions

Based on the results from this study it is concluded that ET_c can be calculated by modifying ET_o values for crop and residual soil moisture conditions using appropriate K_c and K_a coefficients. Minimum K_c was approximately 0.85 in December and January, while a maximum of approximately 1.05 occurred during the months of June and July. Soil water use decreased with soil water content, resulting in K_a values of 1.0 at nearly 15% ASWD to 0.6 at 50% ASWD. With few exceptions, daily soil water uptake per unit root length density was similar for all soil layers. The best correlation between daily water use and soil water content was found in the soil volume containing the highest root length density. Therefore, the hypothesis that soil water uptake relative to calculated reference evapotranspiration is related to season of year, soil water content and root length densities was confirmed. Estimation of soil water uptake and resulting soil depletion based on root length density would allow for a relatively accurate assessment of soil water depletion, crop water status, and effective soil storage capacity using a layer soil profile modeling approach. Such approach would allow model users to predict soil

water depletion throughout a soil profile and assess effective soil water storage capacity and potential leaching of nutrients associated with rainfall and/or irrigation.

CHAPTER 6
CITRUS NITROGEN UPTAKE AND CYCLING

Introduction

The optimum timing, frequency, and rate of fertilizer N application for citrus production under Florida conditions have been explored for nearly 60 years. Nitrogen best management practices (BMPs) have been established for citrus on the sandy soils of central Florida. The goals of these practices are to sustain high fruit production and tree health, and improve N use efficiency of citrus while reducing the impact of N leaching on ground water quality. The BMPs restrict the annual rate of N fertilizer than can be applied, and base it on tree age or past production. The timing of N application is restricted to the drier seasons of the year to reduce potential leaching. A N balance model for citrus must be developed to predict the effects of these restrictions on citrus production.

Koo (1979) found a significant N rate and irrigation interaction in high density planting using low volume microsprinkler irrigation. Koo (1980) later found no yield difference between dry fertilizer N applications and fertigation through the same low volume system. In the same experiment, no yield differences were found when 10 fertigation applications were compared with three dry applications per year. Recent studies by Alva and Paramasivam (1998) and Wheaton (unpublished) have shown similar results. Koo (1986) and Boman (1993) found no difference in yield when comparing multiple applications of dry soluble fertilizer with controlled release N sources.

Syvertsen and Smith (1996) reported that leaching losses were generally small (2 to 9%) from low and medium N rate treatments in a lysimeter study, except when N application coincided with frequent and/or intensive rainfall events. They also concluded that 28% of applied N might have been lost in planted lysimeters due to volatilization and/or denitrification. Immobilization into organic matter by soil microbes was not considered a significant mechanism of N removal due to the very low organic matter content of the Entisol used in the lysimeters. Estimated N uptake was 61% for the high N application rate of 1.6 kg tree^{-1} yr^{-1} and 83% for the lowest application rate of 0.3 kg tree^{-1} yr^{-1}. These values are similar to a previously estimated NUE of 68% (Syvertsen et al. 1993). Lea-Cox and Syvertsen (1996) and Scholberg et al. (2002) reported similar findings of lower NUE with higher N application rate in a greenhouse studies.

Scholberg et al. (2002) found N uptake of greenhouse-grown seedlings to be proportional to soil temperature, potential ET, and canopy biomass. Overall N uptake increased with residence time in the root zone. Alva and Paramasivam (1998) reported improved N use efficiency (0.36 to 0.39 Mg^{-1} fruit per kg N applied) of field grown citrus, which was substantially greater than that reported by Koo and Smajstrla (1984) (0.23 Mg^{-1} fruit per kg N supplied). This improvement was attributed to incorporation of dry and fertigated nutrients under the canopy with light irrigation, applying no fertilizer during the rainy season (between June and August), and maintaining adequate but not excessive soil water content to 90 cm depth.

There is a positive relationship between the concentration of a nutrient in the soil solution at the root surface and its uptake rate by plants. Passive nutrient uptake is defined as the amount of a nutrient taken into a plant as solute associated with water

uptake. The active uptake of nutrients across a membrane is enzyme-catalyzed, thus the relationship of uptake rate to nutrient concentration is hyperbolic with a maximum uptake rate at the nutrient concentration where available enzymes are saturated. The Michaelis-Menten equation (Equation 6-1) is often used to estimate uptake rates for crop plants under given nutrient concentrations.

$$I = I_{max}\, C_{La}\, /(K_m + C_{La})$$ Equation 6-1

Where:

I = inflow flux of nutrient (mol cm^{-2} s^{-1}),

I_{max} = maximum active flux (mol cm^{-2} s^{-1}),

C_{La} = nutrient concentration in the soil solution at the root surface (mol cm^{-3}),

$K_m = C_{La}$ value at I_{max}/2 (mol cm^{-3}),

Numerous reports suggest that actively growing tissues such as young developing leaves and fruit constitute the strongest sink for N uptake (Dasberg, 1987; Feigenbaum et al., 1987; Legaz et al., 1982). Accumulated N was found primarily in fruitlets and newly developed leaves and twigs. Absorption rates increased from the beginning of growth and flowering, reached a maximum at the second shoot growth flush (July), and then declined through dormancy. Only about 20 to 30% of the new leaf and fruit N originated from the labeled source, suggesting considerable redistribution from stored reserves.

Mooney et al. (1992) observed an N concentration gradient between the roots, trunk and branches of citrus trees in New Zealand. High concentrations were found in the branches, with lower concentrations in the roots. Nitrogen concentrations in the trunk were highest at bud break and declined steadily through fruit set and development with a minimum at harvest. Kato et al (1982) found that total N content decreased in both bark

and wood during the sprouting period of 21 year-old 'Satsuma' mandarins. Greatest

decreases in N were found in parts with higher concentrations of N (e.g. leaves, shoots,

and fine roots). They also concluded that the trunk and large roots were main N reservoirs

for new shoot development.

Due to the perennial nature of citrus, leaf, twig and branch biomass accumulated

in previous years periodically abscises. Wallace et al. (1945) estimated that citrus leaves

function on the tree up to 18 to 24 months before senescence. They found an average of

18.1 kg tree^{-1} dry matter loss per year from mature 'Valencia' orange trees grown in

California. Dry matter losses were 9.1, 4.0, and 4.9 kg tree^{-1} for leaves, twigs, and

branches, respectively.

Information on N uptake rates and N cycling for the development of seasonal N

balance under Florida conditions on a field scale is lacking and will be critical to assess N

application quantity, frequency and timing decisions. In order to improve our

understanding of the underlying processes, the following hypotheses were tested: 1)

seasonal N uptake rates are related to leaf N status, 2) fertilizer-N is rapidly converted

into NO_3-N that can be readily leached from typical "ridge soils", 3) leaf N

concentrations are lowest during periods of high growth rate due to N dilution in the dry

matter, 4) changes in tree N reserves account for the majority of N in new leaves, and 5)

tree biomass and N senescence follow predictable seasonal patterns. The main goal of the

current studies was to provide critical information needed for a citrus N budget for a

citrus production system under Florida conditions. The objectives of this study were to 1)

determine seasonal changes in N uptake rates for citrus, 2) quantify changes in residual

soil N and nitrification with time in the absence of citrus roots, 3) measure seasonal

changes in plant tissue N concentration, and 4) determine cumulative tree biomass and N losses for citrus during a 2-year period.

Materials and Methods

Site Characteristics

Fourteen-year-old 'Hamlin' orange on Carrizo citrange and Swingle citrumelo rootstocks at the same location as Experiment 1 in Chapter 3 were used for the three experiments presented in this chapter. The trees had been fertigated at an annual rate of 179 or 269 kg N ha^{-1} at approximately monthly intervals from February to October using equal split applications for the 3 years prior to the start of this experiment. Irrigation was applied by an automated irrigation system using switching tensiometers to trigger irrigations. Irrigation was applied when soil water potential in the upper 30 cm dropped below -10 kPa during the bloom and fruit set period of February to May and -15 kPa for the remainder of the year. Reclaimed water containing 7 mg L^{-1} or less of NO$_3$-N was used for all irrigations. The soil type at the site was Candler fine sand (hyperthermic, uncoated Quartzipsamments) with water holding capacity of 0.05 to 0.08 cm^3 cm^{-3} and cation exchange capacity of less than 5 cmol kg^{-1}.

Experiment 1 - Nitrogen Uptake Flux

Fertilizer rates and applications

The N fertilizer rates used in this study were approximately 50 and 100% of the monthly rate based on 269 kg N ha^{-1} yr^{-1} in 6 monthly applications, or 45 kg N ha^{-1} per application. The 100% rate is equivalent to 500 g N tree^{-1} yr^{-1} or 83 g N tree^{-1} per application. The reduction in N application rate was accomplished by reducing the application time to four representative trees of each rootstock using valves in the

microsprinkler supply lines. After each uptake study, a quantity of N equal to the N reduction was applied to those trees receiving the reduced N rate.

Soil sampling procedures

Fifty 1.27 cm diameter polyvinyl chloride (PVC) pipes were inserted to 45 cm depth beneath the canopy of eight 'Hamlin' on Carrizo and eight 'Hamlin' on Swingle trees at least 2 weeks prior to each study, assuring that all roots within them would die prior to fertigation treatment applications. The pipes were arranged in three semicircles 25, 75, and 125 cm from each tree trunk. The ratio of the lengths of these arcs was 1:3:6. The number of pipes in each arc was proportional to its length, resulting in 5, 15, and 30 pipes in each arc. Soil from these pipes was used as a control to estimate loss of N by volatilization and immobilization in the absence of roots. Changes in NH_4-N and NO_3-N concentrations were used to determine nitrification rates under field conditions.

A composite soil sample consisting of 10 cores taken with a 2 cm diameter auger were removed from each tree at three depth increments of 15 cm each. Samples were taken from the same arcs and ratios where the PVC pipes were installed. Samples were taken 0 h, 1 h, 1 d, 2 d, 3 d, and 4 d after N fertilizer application. The timing of fertilizer applications corresponded with growth phases of the citrus tree when maximum N uptake was most likely: early March (bloom and first spring flush), mid May (second spring flush and fruit expansion), and September (third flush and fruit maturation).

Analytical methods

All soil samples were placed in an insulated cooler containing ice and placed into a refrigerator at 4 C or less until extractions could be made. Extractions using approximately 4 g of soil and 40 mL of 2 M KCl were analyzed to determine soil nitrate (NO_3-N) and ammonia (NH_4-N) concentrations (Keeney and Nelson, 1987). Between 4.1

and 4.3 g of wet soil were placed into a centrifuge tube and the mass was recorded. Forty mL of 2 M KCl was placed into each tube immediately after the soil was weighed. The tubes were placed in a shaker for 1 h. The solution was filtered into vials that were then capped. Extracts were refrigerated at 4 C until they could be analyzed for NO_3-N and NH_4-N. Extracts were analyzed using a model FS3000 Rapid Flow Analyzer (O I Analytical, College Station, Texas). USEPA methods 351.2 and 353.2 were used for ammonium and nitrate analysis, respectively. The remaining soil sample was used to determine gravimetric soil water content of the soil sample extracted.

The N concentration in the soil on a dry weight basis was determined. Volumetric soil water content of each sample was used to determine N concentration in the soil solution. Total N, NH_4-N, and NO_3-N contents in the soil by sample depth were estimated using the soil solution N concentration and area of the irrigation emitter. Daily NH_4-N, and NO_3-N change for each sample depth was determined by comparing daily N content estimates for soil inside and outside of the pipes.

Experiment 2 - Seasonal Tissue N Concentration

Tissue samples were collected from three replicates of 14-year-old 'Hamlin' orange on Carrizo citrange and Swingle citrumelo trees fertilized at an annual rate of 179 or 269 kg N ha^{-1}. Samples were taken at approximately 6 week intervals corresponding to specific stages of growth through the year for two seasons. The growth stages used were 1) bloom and spring flush (early March), 2) fruit drop and second vegetative flush (mid May), 3) first summer flush (early July), 4) second summer flush (mid August), and 5) pre-harvest (mid October). Tissue N concentrations from these samples were determined and used to estimate seasonal change in N concentrations.

Tissue samples collected

The following tissues were sampled at each growth stage: 1) expanding leaves, 2) expanded leaves, 3) twigs (<7 mm), 4) small limbs (7 to 15 mm), 5) medium limbs (15 to 30 mm), 6) large limbs (>30 mm), 7) trunk, 8) feeder roots (<4 mm), and lateral roots (>4 mm). Two trees from each of the 12 plots were selected for each sampling period. Fifty non-expanded leaves per tree were collected from the last flush, and 50 expanded leaves per tree were also collected. Thirty twigs and small (7 to 15 mm) branch segments of 15-30 cm in length were collected. Cylinders of tissue 10 mm in diameter and 15 mm long were removed from branches and trunks greater than 15 mm in diameter using a plug cutter and battery powered drill. Eight plugs from each of four limbs of 15 to 30 mm and >30 mm diameter, and two trunks were collected on each sampling date. Branch and trunk samples were separated into bark and wood components. Twelve fruits were collected on each sampling date. Three soil cores per tree were taken for root removal and roots were separated by size and depth. (size = <4 mm and >4 mm; depth = 0 to 15 cm, 15 to 30 cm, 30 to 45 cm, 45 to 60 cm, and >60 cm).

Tissue analysis

All fresh tissue samples were weighed, dried for 3 days at 70 C, reweighed, and ground for nutrient analysis. Tissues were analyzed for total N using the same grinding and Kjeldahl methods described in Chapter 3. Fruit diameters and leaf area were measured prior to drying.

Experiment 3 - Seasonal N loss

Catch frames 0.9 m wide x 1.5 m long were placed under one tree in each of the 12 plots used for seasonal N concentration determination. Any citrus plant material

falling onto the frames was collected at approximately 2-week intervals for two seasons (2001 and 2002). The plant material was separated into 1) flowers, 2) fruit, 3) twigs, and 4) leaves. Material in each of the four categories was counted, dried, weighted, and analyzed for total Kjeldahl N using the same grinding and analytical procedures described in chapter 3.

Assuming the material collected in the catch frames was proportional to the amount of material under the entire canopy, the biomass and N concentration of each tissue was multiplied by the ratio of the area under the canopy to the area of the catch frame. Cumulative seasonal N loss was determined for each tissue.

Results

Nitrogen Uptake

Irrigation after sampling on the third day after fertilizer application likely leached a portion of the N below the 45 cm sampling depth. Therefore, soil N losses were calculated for the control pipes and bulk soil for 1, 2, and 3 days after application. Differences in mean cumulative N loss from the soil during the 3 days after application were significant at the P=0.05 level for month of year, with greatest loss occurring in May. Soil N losses by rootstock and application rate are presented in Tables 6-1 to 6-3 for the months of March, May, and September, respectively. Mean percentage of total soil N loss during the 3-day period for the high application rate of approximately 83 g tree^{-1} were 60.7, 68.6, and 63.4% for March, May, and September, respectively. These means were significantly different at the P=0.05 level from mean percentage N losses for the lower rate which had respective values of 83.6, 82.6, and 73.1%. Mean cumulative N soil losses for 'Hamlin' trees on Carrizo citrange were 70.5, 78.8, and 70.1% for the

months of March, May, and September, respectively and were not significantly different from mean cumulative losses for trees on Swingle citrumelo, which were 73.8, 72.5, and 66.4% for the same months.

Nitrogen losses from control pipes varied greatly across the three studies but were not significantly affected by application rate, month, or rootstock. Mean cumulative N loss was 22.6%, ranging from a net gain of 7.0% to a loss of 41.0% for the 3 days after application. Estimated daily maximum N uptake was determined by subtracting the N lost from the control pipe from the N lost from the bulk soil. Cumulative daily maximum N uptake was significantly different at the P=0.01 level by application amount, but not significantly different by month, and rootstock (Tables 6-1 to 6-3). Maximum uptake as a percentage of amount applied averaged 46.7 and 61.7% for the high and low application rates, respectively. Mean cumulative maximum uptake values for Carrizo and Swingle were 53.9 and 54.4%, respectively.

Estimated total and passive uptake as a function of mean soil solution N concentration is presented in Figs. 6-1 and 6-2. The equation constants, R^2, RMSE, and P values for the regression of these data are presented in Table 6-4. A great deal of scatter exists in the data due to the large range in N loss from the control pipes. Therefore, the small R^2 indicates that soil solution N concentration explained only 46% of the variation in the data. While both regressions are significant at the P=0.01 level, the relatively large RMSE values would result in a large $100(1-\alpha)$% confidence interval. Using the estimated maximum N uptake and soil solution concentration relationship in Figure 6-1, the Michaelis-Menten equation (Equation 1) constants were approximately 14.5 g N tree^{-1} d^{-1} and 60 mg N L^{-1} for I_{max} and K_m, respectively.

Table 6-1. Estimated cumulative N losses from control pipes and bulk soil, estimated cumulative maximum N uptake, and estimates of passive and active N uptake for samples collected on five consecutive days in March, 2002. Rootstocks are Carrizo citrange, and Swingle citrumelo; high N application rate was 269 kg ha^{-1} yr^{-1}, low rate was 134 kg ha^{-1} yr^{-1}.

Days After Application	Weighted Solution N	N Uptake			Cumulative Total N Uptake		Cumulative N Loss	
		Passive	Active	Total			Control	Soil
	(mg L^{-1})	(g tree^{-1} d^{-1})			(g tree^{-1})	(%)	(% applied)	
		Carrizo – High rate						
1	165.7	5.1	5.1	10.2	10.2	13.9	12.4	26.3
2	152.7	4.5	5.2	9.8	20.0	27.3	27.4	40.8
3	115.8	2.2	7.8	10.0	30.0	41.1	37.3	59.4
		Carrizo – Low rate						
1	80.0	2.9	12.0	14.9	14.9	41.5	0.9	42.4
2	50.6	1.8	5.6	7.4	22.3	62.2	19.6	73.9
3	31.0	0.6	1.8	2.4	24.7	68.8	24.4	81.7
		Swingle – High rate						
1	183.8	5.7	9.0	14.7	14.7	17.9	7.1	25.0
2	181.3	5.4	4.2	9.6	24.3	29.7	7.8	47.3
3	167.1	3.0	10.4	13.4	37.7	46.0	5.4	62.1
		Swingle –Low rate						
1	163.5	5.3	13.8	19.1	19.1	27.2	0.7	28.1
2	124.1	4.5	11.6	16.1	35.2	50.5	16.6	62.6
3	65.8	1.6	10.2	11.8	47.0	67.4	32.7	85.6

Table 6-2. Estimated cumulative N losses from control pipes and bulk soil, estimated cumulative maximum N uptake, and estimates of passive and active N uptake for samples collected on five consecutive days in May, 2002. Rootstocks are Carrizo citrange, and Swingle citrumelo; high N application rate was 269 kg ha^{-1} yr^{-1}, low rate was 134 kg ha^{-1} yr^{-1}.

Days After Application	Weighted Solution N (mg L^{-1})	N Uptake			Cumulative Total N Uptake		Cumulative N Loss	
		Passive	Active	Total	(g tree^{-1})	(%)	Control	Soil
		(g tree^{-1} d^{-1})					(% applied)	
				Carrizo – High rate				
1	156.1	4.6	5.3	9.9	9.9	17.1	8.6	25.7
2	128.7	3.8	8.1	11.9	21.8	37.5	23.2	46.9
3	88.1	1.3	6.1	7.4	29.3	50.3	36.0	65.2
				Carrizo – Low rate				
1	103.3	4.1	17.1	21.2	21.2	42.6	17.7	60.4
2	46.5	1.6	9.7	11.2	32.5	65.2	33.5	89.2
3	20.9	0.3	1.7	2.0	34.4	69.2	26.8	92.5
				Swingle – High rate				
1	195.7	5.6	12.4	18.0	18.0	23.9	-4.5	23.9
2	179.2	4.8	10.5	15.3	33.3	44.1	2.1	59.1
3	139.1	2.2	6.2	8.5	41.8	55.3	5.5	72.0
				Swingle – Low rate				
1	101.1	4.0	11.1	15.2	15.2	31.4	13.6	45.0
2	44.3	1.1	4.9	6.0	21.1	43.7	28.6	65.6
3	22.8	0.3	1.1	1.4	22.5	46.6	41.0	72.7

Table 6-3. Estimated cumulative N losses from control pipes and bulk soil, estimated cumulative maximum N uptake, and estimates of passive and active N uptake for samples collected on five consecutive days in September, 2002. Rootstocks are Carrizo citrange, and Swingle citrumelo; high N application rate was 269 kg ha^{-1} yr^{-1}, low rate was 134 kg ha^{-1} yr^{-1}.

| Days After Application	Weighted Solution N (mg L^{-1})	N Uptake			Cumulative Total N Uptake		Cumulative N Loss	
		Passive	Active	Total			Control	Soil
		(g tree^{-1} d^{-1})			(g tree^{-1})	(%)	(% applied)	
				Carrizo – High rate				
1	187.8	5.8	4.9	10.7	10.7	17.8	0.1	17.9
2	131.6	4.6	5.4	10.1	20.8	34.4	4.1	38.0
3	91.9	3.4	3.7	7.1	27.9	46.3	18.5	58.6
				Carrizo – Low rate				
1	102.6	3.3	4.8	8.1	8.1	24.9	4.9	29.8
2	61.7	2.2	2.7	4.9	13.0	39.8	10.2	48.5
3	28.7	1.5	1.1	2.7	15.6	48.0	19.0	81.8
				Swingle – High rate				
1	201.0	7.8	8.4	16.1	16.2	19.0	22.5	41.5
2	121.1	4.1	5.8	10.0	26.1	30.7	25.1	54.8
3	90.2	3.4	5.6	9.0	35.1	41.3	31.7	68.3
				Swingle – Low rate				
1	118.7	4.2	9.1	13.2	13.2	31.4	1.0	32.4
2	77.4	2.6	8.2	10.8	24.1	57.2	-25.0	40.6
3	55.9	2.2	3.4	5.5	29.6	70.3	-7.0	64.7
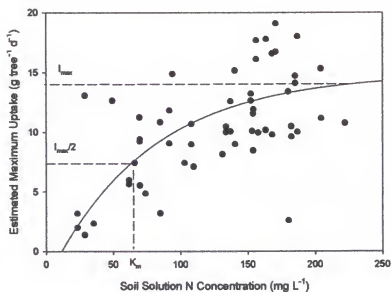
Fig. 6-1. Relationship of estimated total N uptake as a functrion of soil solution concentrations. Total N uptake is the sum of passive and active N uptake components. Dashed lines denote Michaelis-Menten equation constants of I_{max} and K_m.
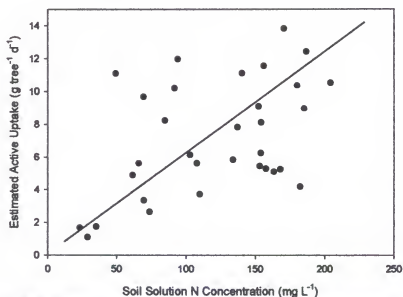

Fig. 6-2. Relationship of estimated active N uptake to soil solution concentration.

Table 6-4. Regression equations for estimated maximum N uptake and estimated active N uptake rates by soil N concentration (mg l^{-1}) using an exponential rise to a maximum model^z and linear model^y, respectively.

Y_0	a	b	R^2	RMSE (g tree^{-1} d^{-1})	P
		Maximum N uptake			
-2.44	17.31	0.013	0.46	3.51	<0.0001
		Active N uptake			
-0.78	0.06		0.63	3.41	0.013

^{z} $Y = Y_0 a(1 - exp^{-bx})$ where X = soil N concentration, and a, and b are regression coefficients

^{y} $Y = Y_0 + aX$ where X = soil N concentration, and a, and b are regression coefficients

Passive N uptake was estimated by determining daily water uptake from the irrigated area to a depth of 45 cm using the water uptake equations presented in Chapter 5. Soil solution N contents were estimated for the same area and depth using the soil N and gravimetric soil water content values from the daily soil samples. Passive N uptake was estimated using the assumption that daily passive N uptake was equal to the product of soil solution N concentration and estimated daily water uptake. Estimated passive N uptake was subtracted from the estimated maximum N uptake to estimate daily active N uptake. The regression of estimated active N uptake and soil solution N concentration was significant at the P=0.05 level (Table 6-4). Due to the compounded error associated with the estimation of passive uptake using the regression equations for water uptake, the associated R^2 was lower than that for soil overall N uptake (Table 6-4). However, the RMSE was similar indicating a confidence interval similar to that of the regression of daily maximum uptake (Fig. 6-1). The relationship of active uptake and soil solution concentration was linear over the concentration range used in this study (Fig. 6.2), so no Michaelis-Menten equation constants could be determined.

Nitrification Estimation

Changes in NO_3-N and NH_4-N content inside the control pipes were used to estimate N loss and nitrification rates with time. Soil NO_3-N, NH_4-N, and total N as a percentage of N applied inside the control pipes are shown as a function of time in Fig. 6-3. Mean NO_3-N content in the upper 45 cm of soil increased 24 h after application to 150.6% of NO_3-N applied. The mean NO_3-N content decreased during the next 48 h to 125.8% of total NO_3-N applied. Content of NH_4-N decreased to 34.0% of that applied after 24 h and steadily declined after application to 16.1% of NH_4-N applied on day 3. The sum of NO_3-N and NH_4-N (total N) declined throughout the period to 73.9% of total N applied. This result indicated that approximately 26.1% of N was lost during the 3-day period due to volatilization of NH_4-N, microbial activity, or incorporation of N into organic matter. Whether some of the immobilized N would become available at a later time is unclear. Part of the N immobilization may be associated with recently decayed root biomass in the control pipes which had relatively low C:N ratio. The length of time that N would be lost at this rate is unclear and would certainly be greater if the fertilizer were not incorporated with water. This loss would be emphasized if dry N fertilizer sources were used. The nitrification rate in this soil was rapid, with a mean of more than 50% of the NH_4-N converted to NO_3-N within the first 24 h. Nearly 85% of applied NH_4-N was converted to NO_3-N in 3 days, assuming all of the N loss was NH_4-N.

Seasonal Tissue N Concentration

Leaf and twig N concentrations followed a cyclic pattern during the 2 years of periodic sampling. Nitrogen values were significantly different at the P=0.05 level by month of year and application rate, but not by rootstock. Therefore, values for specific N rates were
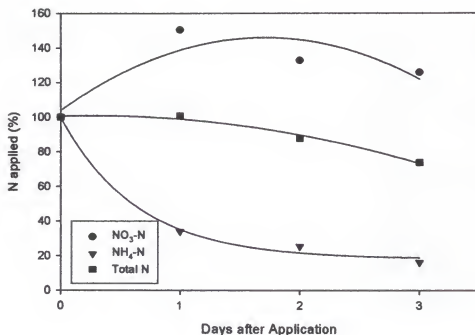
Fig. 6-3. Proportions of nitrate-N, ammonium-N, and total-N from control pipes as percentage applied during 3 days after application. Initial increase in nitrate-N is assumed to be from nitrification of ammonium-N. Low soil pH limits volatilization, thus loss in total-N was assumed to be due to microbial processes.

averaged across rootstocks. Respective N values were near maximum from August to February with minimums in May of each year (Fig. 6-4). Minimum leaf N concentrations were 1.9 and 2.0% for the flush and expanded leaves, respectively, for trees fertilized with 179 kg N ha^{-1} yr^{-1}. Minimum leaf N concentration from trees fertilized with 269 kg N ha^{-1} yr^{-1} were 2.0 and 2.2% for flush and expanded leaves, respectively. Maximum leaf N concentrations were 2.5 and 2.7% for 179 and 269 kg N ha^{-1} annual N application rates, respectively. Leaf areas for both flush and expanded leaves were generally greater for leaves from trees receiving the higher annual N rate (Table 6-5). No such trend was
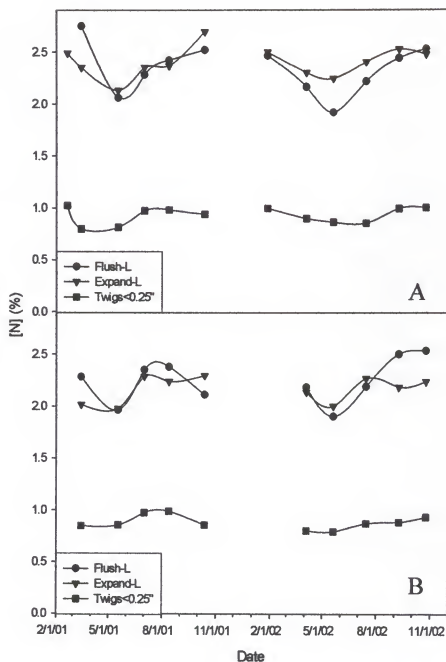
Fig. 6-4. Seasonal change in N concentration for flush leaves, expanded leaves, and twigs during 2001 and 2002. High N rate (A) and Low N rate (B) equal to 269 and 179 kg ha^{-1} yr^{-1}, respectively.

Table 6-5. Seasonal changes in N concentration, size and dry wt. of fruit, flush leaves, and expanded leaves during 2001 and 2002 seasons. There were three replicates of each N rate on two rootstocks (Carrizo citrange and Swingle citrumelo) for a total of 12 measurements per date.

| Date Collected	Fruit [N] (%)	Diameter (mm)	Dry Mass (g fruit⁻¹)	Flush Leaves [N] (%)	Leaf Area (cm² leaf⁻¹)	Dry Mass (g leaf⁻¹)	Expanded Leaves [N] (%)	Leaf Area (cm² leaf⁻¹)	Dry Mass (g leaf⁻¹)
					179 kg N ha⁻¹ yr⁻¹				
3/16/01				2.02	10.0		2.75	33.7	
5/18/01	1.33	38.7	6.0	1.96	21.1	0.2	2.02	32.4	0.38
7/2/01	1.29	51.0	6.3	2.35	25.0	0.2	2.29	29.7	0.39
8/13/01	1.13	62.3	15.1	2.38	22.8	0.2	2.24	30.0	0.36
10/13/01	1.11	66.5	21.0	2.11	20.2	0.2	2.29	41.4	0.38
4/4/02				2.18	28.5	0.2	2.14	33.8	0.33
5/20/02	1.18	36.9	5.6	1.90	15.7	0.3	2.00	32.6	0.51
7/15/02	0.99	53.4	11.1	2.19	20.3	0.1	2.27	20.1	0.21
9/9/02	1.02	63.4	15.0	2.50	23.2	0.2	2.19	26.2	0.23
10/25/02	0.95	65.4	18.2	2.54	22.6	0.2	2.24	28.8	0.25
					269 kg N ha⁻¹ yr⁻¹				
3/16/01				2.75	11.7		2.35	33.3	
5/18/01	1.34	39.5	6.2	2.06	20.7	0.1	2.13	29.0	0.31
7/2/01	1.39	51.5	6.5	2.28	24.9	0.2	2.35	31.4	0.40
8/13/01	1.10	62.1	14.9	2.42	20.6	0.1	2.37	35.0	0.36
10/31/01	0.98	64.1	18.9	2.52	23.8	0.2	2.64	49.5	0.55
4/4/02				2.16	29.2	0.2	2.30	32.2	0.34
5/20/02	1.26	33.8	5.1	1.92	17.2	0.3	2.25	31.9	0.51
7/15/02	0.97	54.0	11.5	2.22	20.0	0.1	2.40	22.5	0.24
9/9/02	1.15	63.9	15.1	2.44	23.8	0.2	2.53	28.7	0.25
10/25/02	1.13	67.3	17.8	2.53	22.9	0.2	2.48	30.3	0.25

apparent for specific leaf weights. Minimum twig N concentrations in May were 0.83% for both annual N application rates. Maximum twig N concentrations were 0.98 and 1.02 % for the 179 and 269 kg N ha^{-1} annual application rates, respectively. These maximums occurred in August.

Branch bark N concentrations remained within a narrow range from 1.0 to 1.3% during the 2-year period (Fig. 6-5). Mean branch bark N concentrations were 1.04 and 1.17% for low and high N application rates, respectively. Minimum values of 1.00 and 1.11% occurred in May or July of each year. Maximum bark N concentrations were 1.09 and 1.22% for low and high annual application rates, respectively. These maximum values occurred in October and January. Branch wood N concentrations were lower, but followed similar trends as those of branch bark tissue (Fig. 6-5). Mean wood N concentrations were 0.25 and 0.31% for the low and high N application rates. Maximum wood N concentrations were 0.37 and 0.38% for low and high N application rates, respectively, and occurred in January and March. Minimum wood N concentrations were 0.23 and 0.29% for low and high N application rates, respectively. These minimums occurred in October.

Root N concentrations were greater for roots <4 mm in diameter than for roots >4 mm. Mean N concentrations for roots <4 mm in diameter were 1.35 and 1.34 % for high and low N application rates, respectively. Mean N concentrations for roots >4 mm in diameter were 0.85 and 0.89% for high and low N application rates, respectively. Seasonal trends of N concentration for roots were not as consistent as with other plant tissues.
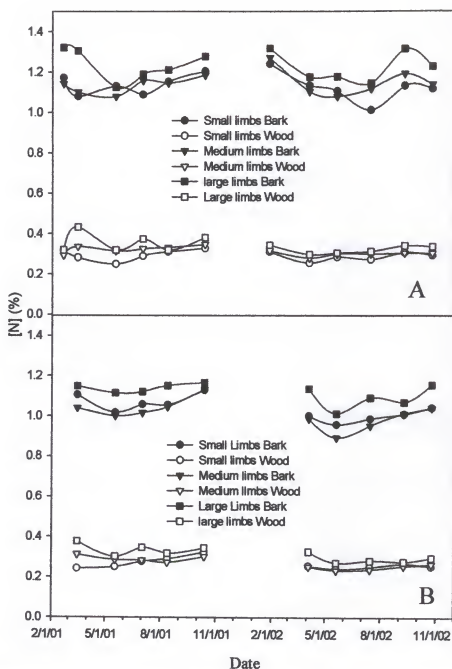
Fig. 6-5. Seasonal changes in N concentrations for bark and wood tissue of small, medium, and large limbs during 2001 and 2002. High N rate (A) and Low N rate (B) equal to 269 and 179 kg ha^{-1} yr^{-1}, respectivel

Fruit N concentration was highest in May of each year at 1.25 and 1.30% for low and high N application rates, respectively (Table 6-5). Nitrogen concentrations decreased through the season to means of 1.03 and 1.06% for low and high N application rates just prior to harvest. Mean fruit diameter did not differ due to N application rate. However, fruit dry masses were greater for the lower application rates.

Seasonal Fertilizer Use Efficiency

Seasonal changes in tree N content from March to May were estimated using the mean biomass values for trees grown on Carrizo and Swingle rootstocks in chapter 3 multiplied by the mean reduction in N for the period. Nitrogen reduction for leaves was 49.0 and 42.6 g tree^{-1} for Carrizo and Swingle trees, respectively. This reduction was relatively large compared with N reduction in twigs and branches of 26.4 and 18.4 g tree^{-1} for trees on the same rootstocks. Thus, total estimated N reduction due to reduction in N concentration from March to May was 75.4 and 61.0 g tree^{-1} for trees grown on Carrizo and Swingle rootstocks, respectively. The amount of tree N gained from spring flush and developing fruit must be added to these values. However, the amount of biomass gained through spring flush was not measured in these studies. It is the author's observation that more biomass is gained in the spring of the year compared with summer vegetative flushes, but the amount of biomass has not been determined. To estimate it, 75% of the reported biomass gained for these trees in 2001 (chapter 3) was used. Biomass values in Table 6-5 indicate that approximately 30% of fruit biomass is accumulated prior to the May sampling. Therefore, 30% of the mean fruit biomass collected prior to the 2002 destructive tree sampling was used as an estimate of fruit biomass gain between March and May. These estimated biomass values were multiplied by the May periodic sampling

N concentration values to estimate the N content of these added biomasses. Estimated leaf and twig flush gains were 108.8 and 95.2 g tree^{-1} for trees grown on Carrizo and Swingle rootstocks, respectively. Fruit N gains amounted to 90.6 and 77.4 g tree^{-1} for the same rootstocks. Nitrogen mass associated with blooms and abscised fruit must also be added and was assumed to be equal to the N loss in blooms and fruitlets. Therefore, the total estimated tree N content increase between March and May was 227.4 and 200.6 g tree^{-1} for trees on Carrizo and Swingle rootstocks, respectively. These N gains would represent a fertilizer use efficiency of 80.8 and 71.3% for Carrizo and Swingle trees, respectively.

'Hamlin' trees gain little leaf and fruit biomass after October of each year. Therefore, using the same methods of estimation with 100% of annual leaf, twig, and fruit biomass gain from Chapter 3, 90.7 g tree^{-1} loss due to senescence was balanced by gains of 471 and 403 g tree^{-1} for trees on Carrizo and Swingle, respectively (Chapter 3). Total net seasonal N content gain was approximately 383 and 312.3 g tree^{-1}, or fertilizer N use efficiencies of 68.3 and 55.7% for trees grown on Carrizo and Swingle, respectively.

Seasonal N loss

Flower, leaf, and fruit were collected from March, 2001 to December, 2002. A relatively small amount of decaying twig and branch material was found in the catch frames at any one time. The majority of these tissues remained attached to the tree until greatly decomposed. Accurate seasonal timing and amount of biomass and N loss from twig and branch material could not be determined without removing all dead twig and branch material at the beginning of the study and periodic removal of dead material from

many trees. Therefore, only blooms, leaves and fruit were included in this study. Seasonal cumulative dry masses and N masses for each of these tissues as a function of time are shown in Figs. 6-6 and 6-7 for 2001 and 2002, respectively.

Bloom dry mass accumulated in March and April of each year. Cumulative senesced flower weights were 529 and 764 g tree^{-1} for 2001 and 2002, respectively. Cumulative flower N masses were 18.8 and 21.9 g N tree^{-1} for the same years. Fruit and leaf biomass losses were greatest from April through May and September through December of each year. Little loss of either of these tissues occurred from June through August.

Cumulative weight loss associated with fruit drop varied more than bloom and leaf biomass, with 1635 and 946 g removed in 2001 and 2002, respectively. These fruit biomass values represented a cumulative loss of 30.1 and 16.8 g of N tree^{-1} for these years. Leaf biomass losses were 2041 and 2806 g tree^{-1} for 2001 and 2002, respectively. Cumulative annual N loss from leaf fall amounted to 42.2 and 51.4 g tree^{-1} for the same years.

Discussion

Seasonal N uptake varied by month of year, with May having the highest uptake rate of the 3 months studied. This result was consistent with other uptake studies using young citrus trees in lysimeters (Syvertsen and Smith, 1996; Lea-Cox et al., 2001), and greenhouse studies (Lea-Cox and Syvertsen, 1996; Scholberg et al., 2002). Increased uptake rates could have been due to higher soil temperature (Scholberg et al., 2002) or greater tree N demand (Dasberg, 1987; Feigenbaum et al., 1987; and Legaz et al., 1982).

Fig. 6-6. Seasonal cumulative dry mass (A) and N content (B) of flowers, fruit, and leaves collected from catch frames under mature citrus trees during the 2001 season.
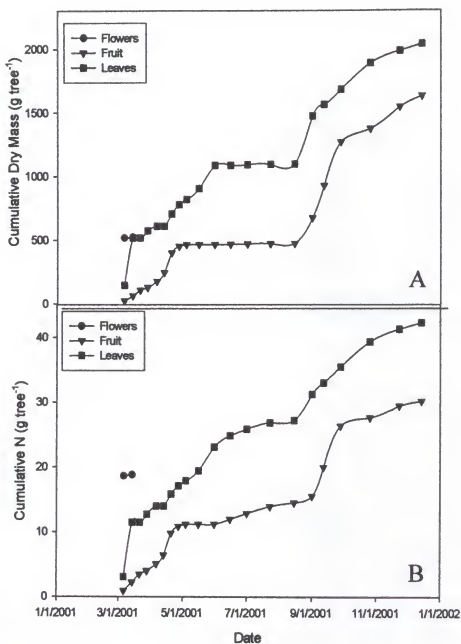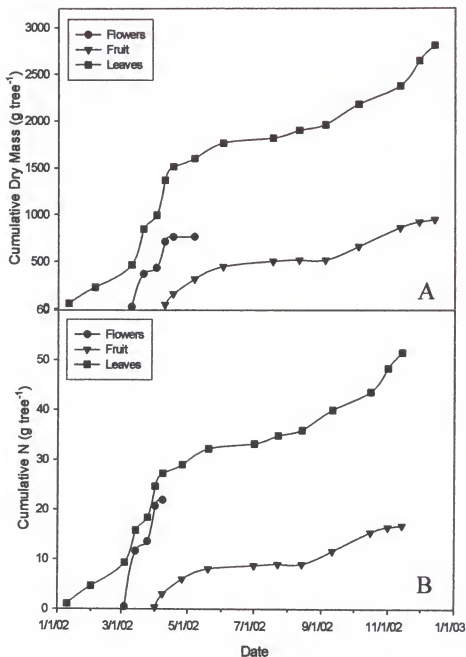
Fig. 6-7. Seasonal cumulative dry mass (A) and N content (B) of flowers, fruit, and leaves collected from catch frames under mature citrus trees during the 2002 season.

Mean daily soil temperature at the 10 cm depth was 5 C higher in May compared with March, 2002. Increased soil N losses in May compared with March and September may be attributed to higher soil temperatures in May.

High N concentrations in leaf, twig and branch tissues have been determined to be sources of N for developing vegetative and reproductive tissues (Dasberg, 1987; Kato et al., 1982; and Legaz et al., 1982). Lower expanded leaf, twig and branch bark N concentrations prior to fertilizer application in May compared with March and September of 2002 agree with results of Kato et al. (1982) and Legaz et al. (1982). This agreement provides evidence of greater crop demand for N during this period of time. Reduced N concentrations in expanding flush leaves may be related to N dilution in the tissue during periods of rapid growth in May. Fertilizer N was added in six equal amounts, four applications in the spring (February, March, April, and May) and two after the end of the rainy season in September and October. Leaf N decreased below optimum concentration prior to the May fertigation application in both years, suggesting that insufficient uptake occurred from February to April to satisfy the N demand of developing tissues. Increases in leaf N concentrations after the May fertilizer application in both years implies that application of all spring N fertilizer should occur prior to May 1 of each year.

Increased active and passive N uptake rates are associated with higher root length densities (Scholberg et al., 2002). Though trees on Swingle rootstocks have more of their root mass in the upper 45 cm than do trees on Carrizo (Chapter 4), significant differences in N uptake by rootstock were not detected. Significantly higher mean daily soil N losses were found for 'Hamlin' trees growing on Swingle compared with 'Hamlin' trees on Carrizo at the high N application rate. However, uptake was lower for Swingle at the

lower application rate. Total uptake rates were nearly equal for trees grown on Swingle and Carrizo at either N application rate.

Numerous studies have been unable to account for 40% or more of total N applied to soils (Mansell et al., 1986, Dasberg et al., 1987). Some authors attributed this unaccounted for fraction as being lost to the atmosphere through denitrification of NO_3-N, while others concluded that the unaccounted for N was either incorporated into soil organic matter or stored in the tree. Using soil of the same type that was used in this study, Lea-Cox and Syvertsen (1993) could not account for 14.5% of ^{15}N applied to containers of soil in the greenhouse at 28 C during the first day. This value increased to 67.0% on the seventh day after application. The loss of ^{15}N was assumed to have been incorporated into microbial biomass because soil pH was too low to account for appreciable volatilization of NH_4-N. These data are similar to the mean of 26.1% N loss in the control pipes 3 days after application. Nitrogen loss after 7 days totaled 60.9% assuming the same rate of loss.

In a lysimeter study by Lea-Cox et al. (2001), 4-year-old grapefruit trees grown in Candler fine sand were fertilized with 2.6, 5.1, and 11.6 g N tree^{-1} of double-^{15}N labeled ammonium nitrate. Soil samples contained no NH_4-N on either date for the lowest rate, and a mean of 58.2 and 0% of the highest rate on 1 and 8 days after application, respectively. This result suggests that the mean of 34.0% NH_4-N found 1 day after application of 85.1 and approximately 43 g N tree^{-1} in the current study is too low. However, in the same study, a mean of only 5.7% of NH_4-N applied at the 5.1 g N tree^{-1} rate was found in soil under trees not contained in lysimeters compared with 17.9% in lysimeters at the same application rate. This result implies that the NH_4-N amounts in the

lysimeters may be 3.5 times too high, reducing the residual NH_4-N amount in bulk soil to 16.6% 1 day after application. If this is the case, then values found in this study are probably similar to those found by Lea-Cox et al. (2001).

In the same study, Lea-Cox et al. (2001) found that tissue accumulation of ^{15}N increased for the first 3 to 5 days after application with little additional subsequent increase, with the exception of trees on 'Volkamer' lemon rootstock. Trees on this rootstock increased in ^{15}N accumulation to between days 7 and 15, but only at the highest N application rate. Young trees on 'Volkamer' lemon grow rapidly and are assumed to have high N demand compared with the two rootstocks used in the current study. This result confirms that both N demand and availability control uptake rates (Dasberg, 1987; Kato et al. 1982, and Scholberg et al., 2002). Lea-Cox et al. (2001) found total N in the soil was reduced by 71.3 to 95.1 of the applied N on day 8 for trees grown on 'Volkamer' lemon rootstock. Assuming that the majority of N is removed and accumulated by the tree in the first 3 to 5 days, a reduction in applied N ranging from 70.1 to 83.6% three days after application for the two rates in the current study would appear to be reasonable. Likewise, the estimated NUE that ranged from 50.2 to 84.0% of the ^{15}N applied after 29 days in the above study was similar to the estimated mean maximum uptake range of 46.7 to 61.7% for the high and low N application rates used in this study.

Mean estimated cumulative dry biomass losses during the 2-year study from flowers, fruit and leaves were 646, 1290, and 2423 g tree^{-1}, respectively. Leaf loss accounted for approximately 33% of the total leaf biomass estimated for mature trees of the same size. This result indicates that leaves could remain on citrus trees for a many as 3 years, which is 1 year longer than reported by Wallace et al. (1945). Leaf longevity

may also be affected by climatic conditions and the incidence of pest and diseases. Cumulative N losses for flowers, fruit, and leaves were 20.3, 23.4, and 49.3 g tree^{-1}, respectively. Assuming that all N from senesced plant parts is incorporated into soil organic matter, and that this rate of N addition is similar to previous years, 93 g or more of N may be available on an annual basis due to mineralization. Using the N balance calculated for mature citrus trees grown on Carrizo and Swingle rootstocks in Chapter 3, 600 g N tree^{-1} could be available to the trees. This amount of N would reduce N uptake efficiency to 78.5 and 67.2% for trees grown on Carrizo and Swingle rootstocks, respectively. These values are near the upper limit of NUE values estimated for citrus in studies by Syvertsen and Smith (1996).

Conclusions

Leaf, twig, and branch bark N concentrations decreased through the spring to minimums in May and June of each year. This time period corresponds to a period of high vegetative and reproductive growth rates. High NUE in May compared with October indicates that the reduction in tissue N concentration is not due to ability of the tree to extract available N from the soil, but possibly a redistribution of N from leaf, twig and branch bark tissues in response to low N supply. Tissue N concentrations recovered by late summer, approaching winter values. Under Florida conditions, NH_4-N was rapidly converted to NO_3-N. Nitrogen uptake rates were greater in late spring when soil temperatures were high and leaf N concentrations were low, compared with late summer when soil temperatures were similar and leaf N concentrations were higher. This relationship indicates a correlation between tissue N concentration and N uptake rates. Such a relationship is fundamental to modeling N uptake in any crop. Tree biomass and

N senescence patterns were relatively consistent across seasons providing a relationship for seasonal tree N balance for citrus. Understanding seasonal N uptake rates and cycling is necessary to develop of crop models. Such models provide a scientific basis for improved water and N management in agricultural production. Providing citrus growers with tools like an expert system to increase NUE and avoid nitrate leaching is essential, especially in Florida due to the low water and nutrient holding capacity of the sandy soils there.

Simulating plant growth is complex due to the interactions of biological processes, soil physical characteristics, and environmental factors (Jones and Luyten, 1998). Biological processes and soil physical characteristics define the crop system and include photosynthesis, respiration, transpiration, biomass accumulation, soil water and nutrient uptake, and nitrogen leaching. Environmental factors such as temperature, radiation, wind, humidity, rainfall, and irrigation influence these processes and are typically required as model inputs. Modeling these processes requires the estimation of many state variables with time through the use of linear or non-linear functions and associated parameters and constants. The goals of this study were to 1) determine changes in above ground citrus biomass and N distribution for trees under recommended N fertility practices over a range of tree sizes, 2) collect information on spatial distribution patterns of citrus root length density for different tree sizes, 3) estimate evapotranspiration crop and soil moisture coefficients, and soil water use per unit root length density, 4) explore seasonal N uptake rates for citrus, and 5) compare seasonal biomass and N concentration changes for citrus fertigated at two annual N fertilizer rates.

Mature Tree Biomass Distribution

Leaf biomass represented 12 to 15% of total tree biomass, while total branch weights were 50 to 65% of total tree weight. Total root biomass was highly variable, but

averaged 20-24% of total tree weight. Mature trees on Carrizo citrange rootstocks were significantly larger than those on Swingle citrumelo. The proportion of large branch biomass with respect to total tree biomass was significantly greater for trees grown on Carrizo compared with trees grown on Swingle. On a percentage basis, taproot biomass was significantly greater for trees on Swingle than those on Carrizo. Mean total biomass of large roots and taproots was greater for trees on Swingle than for those on Carrizo.

Biomass Vs Tree Size Relationships

Total leaf area per tree was proportional to both tree canopy volume and average trunk diameter. Maximum total fresh and dry weights for trees with canopy volumes ranging from 28 to 38 m^3 and trunk cross sectional area of 130 to 150 mm were approximately 160 and 100 kg tree^{-1}, respectively. Above-ground and below ground dry weights of large citrus trees were approximately 74 and 26 kg, respectively. Leaf biomass declined from approximately 20% of total biomass for trees with canopy volumes of less than 5 m^3 and trunk cross sectional area of less than 60 mm to approximately 12% of total biomass for trees with canopy volumes greater than 30 m^3 and trunk cross sectional area greater than 120 mm. Likewise, twig biomass decreased from 11% of biomass to 6% for trees in the same size categories. Total branch dry biomass increased from 15 to 45% across the range of small to large trees, while trunk biomass concurrently decreased from 12 to 3%.

Nitrogen Distribution

As with dry biomass, estimated total N mass was greater for trees on Carrizo rootstock compared with trees on Swingle. Mean leaf, branch, and root N were approximately 45, 35, and 20% of total N for mature citrus trees. Trees grown on Carrizo

accumulated almost 50% more N in large branches compared with trees on Swingle. Total leaf N weight increased from less than 30 to more than 250 g tree^{-1} across the range of canopy volumes and trunk diameters measured. Leaf N accounted for 45% of total N in trees with canopy volumes less than 5 m^3 and 37% of total N in trees greater than 35 m^3. Twig N ranged from less than 10 to greater than 50 g tree^{-1} through the same range of tree sizes. However, unlike leaves, twig N corresponded to a consistent 9% of total tree N. Total branch N weight increased from less than 10 to greater than 200 g N tree^{-1}, which corresponded to an increase in percentage of total tree N from 6 to 27% for the range of tree sizes measured. Concurrently, the proportion of total tree N in the trunk decreased from 5 to 3%.

Mature 'Hamlin' Root Distribution

Average root length density of fine fibrous roots surrounding mature citrus trees followed a bimodal spatial distribution with depth from the soil surface and decreased with distance from the tree trunk. Mean fine fibrous root density in the upper 15 cm was 1.036 cm cm^{-3} and ranged from 1.9 cm cm^{-3} at 50 cm from the tree trunk to 0.7 cm cm^{-3} at the 200 cm distance. Mean densities decreased at the 15 to 30 cm depth to 0.30 cm cm^{-3} ranging from 0.50 to 0.07 cm cm^{-3} at 50 and 200 cm distances, respectively. Mean densities of fine fibrous roots increased with subsequent depths to a maximum at the 60 to 75 cm depth and then declined at the 75 to 90 cm depth.

Differences in root spatial distribution between rootstocks were not statistically significant. Mean root length densities at all depths and distances were 0.36 cm cm^{-3} for trees grown on Carrizo citrange and 0.41 cm cm^{-3} for trees grown on Swingle citrumelo. Trees grown on Swingle had greater root length densities near the soil surface than did

trees on Carrizo. Conversely, root length densities were greater for trees on Carrizo between 15 and 75 cm below the soil surface. Root length densities increased for trees on Carrizo at the 45 to 60 cm depth, whereas densities for trees on Swingle increased at the 60 to 75 and 75 to 90 cm depths.

Root Length Density Distribution Changes with Tree Size

Distance from the tree trunk and depth from the soil surface significantly affected citrus root length density across a wide range of tree sizes. Root systems of young trees were initially concentrated at the soil surface, with few roots deeper than 0.5 m at a distance of 150 cm from the tree trunk. As the citrus trees began to produce fruit (5 to 10 years of age) root length density increased at the soil surface to a distance equal to the dripline of the tree. Roots extended to the 200 cm distance between tree rows and to a depth of 0.9 m at 150 cm from the trunk. The bimodal nature of the root system was observed close to the trunk at depths below 60 cm. By the time trees reached 10 to 15 years of age and the canopy was nearing a full hedgerow, the bimodality of the root system was fully developed and roots extended below 1m at all distances from the tree.

Seasonal ET_o and ET_c Trends

Daily ET_o reported by FAWN for the experimental site ranged from a minimum of 1.12 mm in December 2001 to a maximum of 6.48 mm in June 2001. Monthly maximum, minimum, and mean ET_o and ET_c were not significantly different for the same months during the 2 years of this study. Although generally lower, daily ET_c followed the same seasonal patterns as ET_o. The exception to this correlation occurred during the summer months of June through August, and then only when soil was near field capacity.

Seasonal K_c

The ratios of ET_c to ET_o at field capacity were used to estimate K_c. The ET_c to ET_o ratios ranged between 0.81 on DOY 24 and 1.12 on DOY 179. With an R^2 of 0.755, DOY explained more than 75% of the variation in the ET_c to ET_o ratios when soil water content was near field capacity. Therefore, the results of the equation are a good approximation of the value of K_c for a given DOY.

K_s Estimation

The relationship of estimated K_s to available soil water depletion (ASWD) and soil water potential was logistic in nature with a value of 1 from field capacity to approximately 10 to 15% of ASWD. The relationship decreased steadily to approximately 0.6 at 50% ASWD, indicating a reduction of 40% in ET_c between 15 and 50% ASWD.

Soil Water Uptake per Unit Root Length

An exponential decay model resulted in the best fit of unit root length uptake to soil water potential with a maximum of approximately 0.4 mm^3 d^{-1} cm^{-1} at field capacity. Daily ET_c per unit root length decreased rapidly with decrease in soil water potential to -12 or -13 kPa, followed by a more gradual reduction from approximately 0.1 to 0.05 mm^3 d^{-1} cm^{-1} well past -20 kPa. Higher water uptake per unit root length values at field capacity were found at the 10 cm depth between rows. This value was double that observed at other locations and depths. The increase in water uptake could be explained by water use from non-crop species in the row middles that were not present beneath the tree canopy.

Nitrogen Uptake

Differences in mean cumulative N loss from the soil 3 days after fertilizer application were significantly influenced by month of year, with the greatest loss in May. Mean percentage of total soil N loss during the 3 day period for the high (83 g N tree^{-1}) application rates were 60.7, 68.6, and 63.4% for March, May, and September; respectively. These means were significantly different from mean percentage losses for the lower N rate, which were 83.6, 82.6 and 73.1% for the same three months. Mean cumulative N soil losses for 'Hamlin' trees on Carrizo citrange were 70.5, 78.8, and 70.1% of N applied for the months of March, May, and September, respectively, and were not significantly different from mean cumulative losses for trees on Swingle citrumelo, which were 73.8, 72.5, and 66.4% of total N applied for the same months.

Nitrogen losses from the control treatment varied greatly in the three studies and were not significantly different by application rate, month, or rootstock. Mean cumulative N loss was 22.6%, and ranged from a net gain of 7.0% to a loss of 41.0% during the 3 days after fertilizer application. Cumulative daily maximum N uptake was significantly different by application amount, but not significantly different by month and rootstock. Maximum uptake as a percentage of amount applied averaged 46.7 and 61.7 for the high and low application rates, respectively. Mean cumulative N uptakes for Carrizo and Swingle rootstocks were 53.9 and 54.4%, respectively. Estimates of the Michaelis-Menten equation constants I_{max} and K_m for active N uptake were 8.5 g tree^{-1} d^{-1} and 45 mg L^{-1}, respectively.

Nitrification Estimation

Mean NO_3-N content in the upper 45 cm of soil increased 24 h after application to 151% of NO_3-N applied. The mean NO_3-N content decreased during the next 48 h to 126% of total NO_3-N applied. Content of NH_4-N decreased to 34% of that applied after 24 h and steadily declined after application to 16% of NH_4-N applied on day 3. The sum of NO_3-N and NH_4-N (total mineral N) declined throughout the period to 73.9% of total N applied on day 3, indicating that approximately 26.1% N was lost in 3 days due to volatilization of NH_4-N, microbial activity, or incorporation in organic matter. The nitrification rate in this soil was very rapid. With an average of more than 50% of the NH_4-N converted to NO_3-N within the first 24 h, nearly 85% of applied NH_4-N was converted to NO_3-N in 3 days assuming all of the N loss was NH_4-N.

Seasonal Tissue N Concentration

Leaf and twig N percentages were near maximum from August to February and at minimum in May of each year. Minimum leaf N concentrations were 1.9% and 2.0% for the flush and expanded leaves, respectively, on trees fertilized with 179 kg N ha^{-1} yr^{-1}. Minimum leaf N concentration for trees fertilized with 269 kg N ha^{-1} yr^{-1} were 2.0 and 2.2% for flush and expanded leaves, respectively. Maximum leaf N concentrations were 2.5 and 2.7% for 179 and 269 kg ha^{-1} annual application rates, respectively. The areas of both flush and expanded leaves were generally greater for trees receiving the high annual N rate. Minimum twig N concentrations occurred in May and were 0.83% for both annual N application rates. Maximum twig N concentrations of 0.98 and 1.02% for the 179 and 269 kg N ha^{-1} annual application rates, respectively, occurred in August.

Branch bark N concentrations were consistently in a narrow range of 1.0 to 1.3% during the 2-year period, with means of 1.04 and 1.17% for low and high N application rates, respectively. Minimum bark N concentrations of 1.00 and 1.11% occurred in May or June of each year, while maximum concentrations of 1.09 and 1.22% occurred in October and January for low and high annual N application rates, respectively. Branch wood N concentrations were lower, and followed trends similar to those of branch bark tissue. Mean wood N concentrations were 0.25 and 0.31% for the low and high N application rates, respectively. Maximum wood N concentrations were 0.37 and 0.38% for the same rates, respectively, and occurred in January and March. Minimum wood N concentrations were 0.23 and 0.29% for low and high N application rates, respectively, and occurred in October.

Root N concentrations were greater for roots <4 mm in diameter compared with larger roots. Mean N concentrations were 1.34 and 1.35% for low and high N application rates, respectively, for roots <4 mm in diameter. Mean N concentrations for roots >4 mm in diameter were 0.85 and 0.89% for the same rates. Fruit N concentration was highest in May of each year (1.25 and 1.30% for low and high N application rates, respectively). Nitrogen concentrations decreased through the season to means of 1.03 and 1.06% for low and high N application rates, respectively, just prior to harvest. Mean fruit diameter was not constantly different by N application rate. However, fruit dry weights were greater for the lower application rate.

Seasonal Nitrogen Loss

Flower dry weight accumulated in March and April of each year with cumulative weights of 529 and 764 g tree^{-1} for 2001 and 2002, respectively. Cumulative flower N

weights were 18.8 and 21.9 g tree^{-1} for the same years. Fruit and leaf biomass losses were greatest in April through May and September through December of each year. Little loss of either of these tissues occurred from June through August. Cumulative fruit biomass varied more than bloom and leaf biomass, with 1635 and 946 g tree^{-1} removed in 2001 and 2002, respectively. These fruit biomass values represented a cumulative loss of 30.1 and 16.8 g tree^{-1} of N for these years. Leaf biomass losses were 2041 and 2806 g tree^{-1} for 2001 and 2002, respectively. Cumulative annual N loss from leaf fall amounted to 42.2 and 51.4 g tree^{-1} for the same years.

Citrus Decision Support System

Due to the complexity of grower decision-making processes, researchers have developed computer based decision support systems (DSS) to provide information on management options. These DSS store and organize information such as rates of water, fertilizer, and agrichemicals applied to specific fields and provide information on predicted future events such as irrigation scheduling and N leaching. Crop models are used to determine the effect a given management decision will have on the crop such as growth rate or yield. Crop models such as CROPGRO, CERES and others (Hoogenboom et al., 1994; Jones et al., 1991; Wagner-Riddle et al., 1997) are process-oriented models that simulate vegetative growth and reproductive development. The models predict dry matter growth (Shen et al., 1998), crop development (Batchelor et al., 1994; Batchelor et al., 1997; Piper et al., 1996) and final yield (Batchelor et al., 1996; Heinemann et al., 2000) for a range of agronomic crops. Inputs are daily weather data, soil profile characteristics, and crop management conditions (Gijsman et al., 2002). Such models are currently being used for a number of purposes such as yield forecasting and long-term

effects of crop sequencing under given management inputs and weather conditions. Crop and soil water status (Hoogenboom et al., 1994; Gabrielle et al., 1995; and Xie et al., 2001) and N and C balances (Gabrielle and Kengni, 1996; Quemada and Cabrera, 1995; and Sexton et al., 1998) have been modeled. These models can combine with crop developmental models of irrigation scheduling, fertilizer N fate determination, and nitrate leaching estimates. A DSS can provide the framework for storing of information needed by the model and can include a user-friendly output to assess production options.

Citrus production would benefit greatly from such a DSS. Data collected and relationships determined in this dissertation as well as literature sources can provide information required to model seasonal and temporal citrus N demand, root development processes, seasonal water and N uptake, and seasonal N distribution. These models can lead to a DSS capable of providing irrigation scheduling, fertilizer requirements and rates, and environmental impacts of nitrate leaching. Verification of best management practices and grower compliance with such practices can be determined using a DSS. The ultimate goal of such a DSS would be the improved allocation of water and fertilizer resources for optimal yield with minimal environmental impact.

Citrus N Practices and BNPs

Florida's population has increased from 3 million in 1950 to more than 16 million at present, creating severe competition between agricultural, commercial, residential, and environmental users for Florida's limited water resources. As a result of increased demand, consumption and quality of water has become highly scrutinized by regulators. Improvements in both N uptake efficiency and timing of N applications to coincide with N demand will balance the needs of the citrus tree while minimizing water quality

impacts. This study has improved our understanding of seasonal and long-term N accumulation by citrus. The information generated will be essential to refine citrus N BMPs using sound, science-based decision making. Improved BMPs will allow for sustainable productivity while safeguarding the environment from leaching of excess NO_3-N to ground water.

Current citrus N BMPs base the fertilizer N application rate on the chronological age of young citrus trees and stress N fertilization timing in the spring and fall of the year to avoid potential leaching during the summer rainy season. Long-term N accumulation measured in this study indicate that tree size is a more useful method of determining potential N demand of young trees than tree age. Likewise, seasonal N demand by mature citrus trees was greatest during the spring of the year; therefore a citrus N balance will provide a better basis to accurately determine N fertilizer requirements of mature trees.

Soil water content and labile N concentration in the root zone are keys to N uptake efficiency of citrus. Florida's sandy soils hold little water and dry quickly, reducing potential evapotranspiration much more rapidly than finer textured soils. This decrease in potential uptake impacts passive and active N uptake through reduced water uptake and N diffusion to the root boundary. Therefore, soil water content and N concentrations in the soil volume containing the highest root mass must be maintained as high as practical without forcing N below the root zone. This study showed that two rootstocks thought to have similar root growth patterns in reality had different root densities with distance from the tree and with soil depth. The implication of this finding is that the top 30 cm soil layer may be more critical for water and N fertilizer management for trees on Swingle citrumelo than for trees on Carrizo citrange.

Determining root system distribution patterns of the various rootstocks on which citrus is propagated is essential to irrigation scheduling for improved fertilizer N uptake efficiency.

While current N BMPs are believed to reduce N leaching below the citrus root zone, more accurate methods of determining annual fertilizer N rates, application timing, and irrigation scheduling are essential to improve uptake efficiency and enhance environmental protection. This study confirmed that the basic principles used to derive citrus N BMPs are sound, but also generated data suggesting that refining and fine-tuning BMPs may be necessary to make them totally effective. Adoption of the N balance approach to fertilization evapotranspiration-based irrigation scheduling, and rootstock specific N fertilizer management are essential to sustainable productivity and improved ground water quality.

APPENDIX A
EQUATIONS

$$\upsilon = -K \, d\phi / dx$$

Where:

υ = water flux ($cm^3 \, cm^{-2} \, s^{-1}$),

K = hydraulic conductivity constant ($cm \, s^{-1}$),

ϕ = soil water potential (kPa), and

x = the distance over which the flux is maintained (cm).

$$f = (\pi \, r^4 / 8\eta) \, dP/dx$$

Where:

f = flow rate in a tube ($m^3 \, s^{-1}$),

r = radius (m),

η = viscosity ($\mu Pa \, s^{-1}$), and

dP/dx = pressure gradient.

$$\upsilon = -K_\theta \, d\phi/dx = -K_\theta \, (d\phi/d\theta) \, (d\theta/dx) = -D_\theta \, (d\theta/dx)$$

Where:

υ = water flux ($cm^3 \, cm^{-2} \, s^{-1}$),

K_θ = hydraulic conductivity constant at θ (cm s^{-1}),

ϕ = soil water potential (kPa),

θ = soil water content (cm^3 cm^{-3}),

$d\theta/d\phi$ = slope of the soil characteristic curve, and

x = the distance over which the flux is maintained (cm).

$$TCV = \frac{\pi}{4} * Ir * Cr * Ht * \frac{(1 - (1 - (\frac{Int}{Ht})^2))}{3}$$

Where:

TCV = Tree canopy volume (m^3)

Ir = In-row spacing (m)

Cr = Cross-row spacing (m)

Ht = Canopy height (m)

Int = Canopy intercept height (m)

$ET_c = ET_o * K_c * K_s$

Where:

ET_c = Crop evapotranspiration (mm d^{-1})

ET_o = Potential evapotranspiration (mm d^{-1})

K_c = Crop coefficient

K_s = Soil stress coefficient

$$K_s = \frac{TAW - \theta}{TAW - RAW}$$

Where:

Ks = Soil water stress coefficient

TAW = θ_{FC} - θ_{PWP} = Total available water (cm^3 cm^{-3})

θ = Soil water content (cm^3 cm^{-3})

RAW = θ_{FC} - θ_{RA} = Readily available water (cm^3 cm^{-3})

$I = I_{max} \, C_{La} / (K_m + C_{La})$

Where:

I = inflow flux of nutrient ($mol \, cm^{-2} \, s^{-1}$),

I_{max} = maximum active flux ($mol \, cm^{-2} \, s^{-1}$),

C_{La} = nutrient concentration in the soil solution at the root surface ($mol \, cm^{-3}$),

K_m = C_{La} value at $I_{max}/2$ ($mol \, cm^{-3}$),

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is full adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.
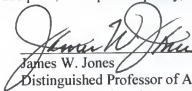
Thomas A. Obreza, Chair
Professor of Soil and Water Science

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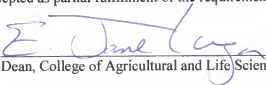
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This dissertation was submitted to the Graduate Faculty of the Collage of Agricultural and Life Sciences and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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